Department of Electronics

Development and analysis of road lighting – Road surfaces and mesopic dimensioning

Anne-Mari Ylinen

Aalto University

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Abstract

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Abstract

This work starts with a short introduction in which the energy consumption, proportion of different types of light sources, and procedures that have been introduced concerning energy saving in outdoor lighting are overviewed. It is followed by a historical review and research related to aspects of the topic referred to in this work: the luminance method used for photometric dimensioning of road lighting, road surface classification practises, and mesopic photometry.

The work continues with a study of road surface reflection characteristics. Road surface reflection measurements were made to study the current state of the pavement materials used on Finnish roads. Pavement samples were extracted from roads and the reflection tables of the pavement samples were measured.The pavement materials used in Finland are somewhat dark and diffuse and the standard reflection tables give an adequate fit for the degree of specularity but not for the degree of lightness.

The spectral reflection properties of various types and differently coloured pavement samples were studied. The results indicate that light sources that have a higher spectral light output in the longer wavelength region, such as high pressure sodium lamps, are more energy–efficient in terms of light reflected from the pavements compared to the ones with a high output in the short wavelength region. In addition, pavement materials made out of recycled materials and local limestone were studied. Light pavement materials reflect more light than darker pavement materials, and energy could be saved by increasing the spacing of the poles for the luminaires or reducing the power consumption of the luminaires.

The work continues with a study of mesopic dimensioning in road lighting. The luminous efficacy of various types of luminaires and the use of mesopic dimensioning in road lighting design were studied. The study is followed by a case study where high pressure sodium lamp street lighting was changed to LED street lighting. The energy consumption of the installation was calculated and mesopic dimensioning was used. The results show that energy savings are possible when mesopic dimensioning is used by reducing the power consumption of the luminaire or by increasing the spacing of the poles for the luminaires.

The work continues by studying the differences in using the standard r-tables and the measured r-tables of the pavement used in the road lightning design on Finnish roads. It was found that the R2 table should be used for road lighting design if the reflection property of the pavement is not known. The work is followed by a study of the use of light pavement materials and mesopic dimensioning. In this case the benefits of mesopic dimensioning are negligible when light pavement materials are used.

Keywords road lighting, road surfaces, mesopic dimensioning

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Tiivistelmä
Työ alkaa lyhyellä johdannolla ulkovalaistuksesn energian käytöstä ja valonlähteiden jakautumisesta eri valolähteiden kesken. Työ jatkuu historiallisella tarkastelulla luminanssimenetelmän käytöstä tievalaistuksen laatukriteerinä, päällysteiden heijastuominaisuuksia kuvaavien parametiren kehityksestä sekä eri fotometrian kehityksestä. Lisäksi työssä käsitellään tievalaituksen energiatehokkuutta myös mesooppisen mitoituksen avulla.

Työ jatkuu tutkimalla päällysteiden heijastusominaisuuksia. Suomessa käytettävien päällysteiden heijastusominaisuuksia ja niiden r-taulukkojen sopivuutta standardin mukaisiin r-taulukoihin verrataan analysoimalla päällystenäytteistä laskettuja heijastuskuvaajia ja standardedien r-taulukoiden heijastuskuvaajia keskenään. Tulosten mukaan Suomessa yleisesti käytettävät tien päällysteet ovat tummia ja hajaheijastavia ja standardi r-taulukot antavat kohtuullisen hyvän kuvan päällysteiden peilimäisuudestä, mutta eivät vaalaus-asteesta.

Työ jatkuu tutkimalla päällysteiden spektraalista heijastavuutta erilaisen ja eriväristen päällystenäytteiden avulla. Tulosten mukaan valonlähteet joilla on suurempi suhteellinen spektrijakauma näkyvän valon pitkällä aallonpituusalueella (esimerkiksi suurpainenatriumlamput) ovat spektraalisen heijastussuhteen mukaan energiatehokaampia tievalaistuksen kannalta. Lisäksi tutkittiin kierrätysmateriaalista ja paikallisesta kalkkikivestä valmistettujen vaaleiden päälysteiden heijastusominaisuuksia ja tulosten mukaan vaaleita päällysteitä käyttämällä voidaan valaisimen energiankulutusta laskea tai kasvattaa valaisimen pylväsväliä.

Työ jatkuu mesooppisen mitoituksen soveltamisella tievalaistuksessa. Valonlähteiden valotehokkuuksia sekä eri tievalaistusluokkien valaistusvaatimuksia tutkittiin mesooppisen mitoituksen kannalta. Tapaustutkimuksena tutkittiin kohdetta, jossa suurpainenatriumlamppuvalaisimet vaihdettiin LED valaisimiin ja valaistuksen energiatehokkuutta verrattiin alkuperäisen asennuksen energiankulutukseen. Valaistuksen energian käyttö laskettiin myös mesooppisen mitouituksen mukaan tehdylle asennukselle. Tulosten mukaan mesooppisella mitoituksella voidaan säästää energiaa joko säätämällä valaistustasoa tai pylväsväliä pidentämällä.

Työssä verrattiin keskenään tievalaistusasennuksia, jotka oli suunniteltu sekä Suomessa käytettyjen päälysteiden r-taulukoiden avulla että standardin mukaisilla r-taulukoilla. Tulosten mukaan valaistussuunnitelma tulisi tehdä luokan R2 päällysteellä, mikäli päällysteen heijastusominaisuuksia ei ole tiedossa. Lisäksi työssä tarkasteltiin vaaleiden päällysteiden vaikutusta mesooppisessa mitoituksessa. Vaaleita päällysteitä käyttämällä pylväsväli voi kasvaa suureksi ja luminanssin tasaisuusarvot on vaikeampi saavuttaa, mikäli pylväsväliä vielä kasvatetaan. Mesooppisen mitoituksen edut eivät ole suuret vaaleita päällysteitä käytettäessä.

Avainsanat tievalaistus, tienpäällysteet, mesooppinen mitoitus

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Preface

The research work in this thesis was conducted at the Lighting Unit of the Aalto University School of Electrical Engineering. Part of the work was carried out in the project “SolarLED” funded by the Finnish Funding Agency for Technology and Innovation, the Finnish Transport Agency, the City of Helsinki , the City of Espoo, The City of Vantaa, the City of Tampere, the City of Porvoo, Helsingin Energia, Oy Turku Energia – Åbo Energi Ab, SITO Oy, Philips Oy, Oy Osram Ab, Naps Systems Oy, iGuzzini Finland & Baltic Oy, Easy Led Oy, Lumi Group Oy, Valopaa Oy, Oy Modines Ltd, Tepcomp Oy, Laukamo Plastcomp Oy, Insinööritoimisto Lausamo Oy, and Sähkötekniikka Oy.

It would not have been possible to write this thesis without the help and support of my colleagues, my family, and my friends.

I am grateful to my supervisor Professor Liisa Halonen for her support and encouragement throughout the whole process. I am also grateful to my instructor Dr Marjukka Puolakka for the priceless help and guidance during the production of this work.

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Espoo, November 2011

Anne Ylinen

List of publications

I A. Ekrias, A.-M. Ylinen, M. Eloholma, L. Halonen, "Effects of pavement lightness and colour on road lighting performance", in *CIE Int. Symp. Road surface photometric characteristics*, Turin, Italy, 2008, 8 p.

II A. Ylinen, M. Eloholma, L. Halonen, "Road surface reflection properties and applicability of the *r*-tables for today's pavement materials in Finland", *Light & Engineering*, vol. 18, no. 1, pp. 78-90, 2010.

III A.-M. Ylinen, T. Pellinen, J. Valtonen, M. Puolakka, L. Halonen, "Investigation of Pavement Light Reflection Characteristics", *Road Materials and Pavement Design*, vol. 12, no. 3, pp. 584-614, 2011.

IV A.-M. Ylinen, M. Eloholma, L.Halonen, "Impact of mesopic design on outdoor lighting energy efficiency", in *CIE Int. Symp. Lighting Quality & Energy Efficiency*, Vienna, Austria, 2010.

V A.-M. Ylinen, L. Tähkämö, M. Eloholma, L. Halonen, "Road lighting quality, energy efficiency and mesopic design – LED street lighting case study", *Leukos*, vol. 8, no. 1, pp 9-24, 2011.

VI A.-M. Ylinen, G. Bizjak, M. Puolakka, L. Halonen, "Road Lighting Practices and Energy-Efficiency – Slovenia and Finland", *Ingineria Iluminatului – Lighting Engineering,* vol. 13, no. 1, pp. 29-44, 2011.

The author played a major role in all the stages of the work presented in this thesis. The author was responsible for collecting the background information and the author participated in the measurements for publication I. The author was responsible for publications II – VI as the main author. The author was responsible for the background information of the road lighting part, the measurements, the calculations and data analysis in publication III. The author was responsible for the calculations in publication IV. The author was responsible for the background information, case measurements, and cost calculations, excluding the cost analysis part, in publication V. The author was responsible for the background information and analysis for the Finnish part in publication VI.

Contents

List of abbreviations and symbols

Abbreviations

AB	asphalt concrete
ADT	average daily traffic
AL4b	Finnish lighting class
C1,C2	C road surface class
CFL	compact fluorescent lamp
CIE	Commission Internationale de l'Eclairage International Commission on Illumination
DBA	closed asphalt concrete
DIALux	lighting design software
EC	European Commission
EN	European Norm
EU	European Union
HDR	high dynamic range
Hilja	noise-reducing pavement
HID	high intensity discharge
HPM	high pressure mercury
HPS	high pressure sodium
LabSoft	lighting measuring software
LED	light emitting diode
LEM	lumen effectiveness multiplier
LPS	low pressure sodium
MEW4	European lighting class for wet surface
ME3c	European lighting class
ME4a, ME4b	European lighting class
ME5	European lighting class
MH	metal halide
MOVE	Mesopic Optimisation of Visual Efficiency
N1 - N4	N road surface class
PAB-V	soft asphalt concrete
PANK ry	Päällystealan neuvottelukunta ry (corporation that coordinates the road construction industry in Finland)
R1 - R4	R road surface class
S2	European lighting class for pedestrian ways
SD	surface dressing
SMA	stone mastic asphalt
VTAC	very thin asphalt concrete
W1 - W4	W road classes

ZOAB	very open asphalt concrete

Symbols

CCT	correlated colour temperature [K]
E_{ave}	average illuminance [lx]
E_{min}	minimum illuminance [lx]
L	luminance [cd/m^2]
L_o	luminance of the reference surface [cd/m^2]
L_{ave}	average road surface luminance [cd/m^2]
L_{mes}	mesopic luminance [cd/m^2]
L_p	photopic luminance [cd/m^2]
P	power [W]
q	luminance coefficient
$q(\gamma,\beta)$	luminance coefficient as a function of angles γ and β
Q_o	average luminance coefficient
r-table	table of reduced luminance coefficients
S	luminaire pole spacing [m]
S/P -ratio	scotopic/photopic –ratio
$S1$, $S2$, S1’	specular factor
SR	surround ratio
TI	threshold increment [%]
U_o	overall luminance uniformity
$U_{o,wet}$	overall luminance uniformity for wet road surface
U_l	longitudinal luminance uniformity
$V(\lambda)$	CIE photopic spectral luminous efficiency function
$V'(\lambda)$	CIE scotopic spectral luminous efficiency function
x	Cartesian x coordinate
y	Cartesian y coordinate
z	Cartesian z coordinate
α	angle of observation
β	angle between plane of light incidence and plane of observation
γ	angle of light incidence
δ	angle between plane of observation and road axis
ρ	reflectance

1 Introduction

1.1 Background

Lighting accounts for 19% of the total global electricity consumption and 14% in the European Union (EU) [**1**]. Outdoor lighting uses around 8% of the total electricity consumption globally [**1**]. The total net electricity generation is expected to grow by 2.3% per year by 2035 and 1.1% per year in Europe [**2**]. The potential for improving the energy efficiency of outdoor lighting is immense. The saving potential in road lighting energy consumption is 25% - 50 % [**3**]. Around 30% of the installed road lighting is based on technology developed before 1970 and around 3% of the road lighting is renewed annually [**4**]. In the EU, the light sources used in road lighting are high pressure mercury (HPM) lamps (32%), high pressure sodium (HPS) lamps (47%), low pressure sodium (LPS) lamps (9%), metal halide (MH) lamps (3%), and compact fluorescent (CLF) lamps (8%) [**5**].

In Finland, the estimated annual energy consumption of outdoor lighting is 800 GWh [**6**], which accounts for 1% of the country's total electricity consumption. The estimated number of outdoor luminaires is 1.3 million of which 51% are high pressure mercury (HPM) lamp luminaires and 45% are high pressure sodium (HPS) lamp luminaires. The rest are low pressure sodium (LPS) lamp luminaires, metal halide (MH) lamp luminaires and induction lamp luminaires. The average lifetime of a street lighting luminaire is around 30 years [**5**]. Therefore, the lighting installations may no longer comply with the photometric requirements.

There are also some light emitting diode (LED) road lighting installations in Finland. These installations are mostly test cases and consist of only a small number of luminaires.

Saving energy in outdoor lighting is a big issue in many countries. In Finland, dimming or turning off every other luminaire during the hours of darkness are most commonly used and intelligent road lighting control systems are being used in some test installations. In order to reduce the energy consumption of lighting the European Union has adopted the Directive of Ecodesign of Energy-Related Products (Directive 2009/125/EC) [**7**] which establishes the framework for setting the ecodesign requirements for energy-related products. The purpose of the Directive is to improve the environmental performance of products throughout their life cycle. The directive does not give requirements for specific product categories, but defines the procedure for setting the requirements in implementing measures. The requirements concentrate on the most important environmental aspects such as the energy consumption of energy-using products. Commission Regulation (EC) No. 244/2009 [**8**] and Commission Regulation (EC) No. 245/2009 [**9**] concern the lighting sector. Regulation No. 244/2009 refers to non-directional light sources typically used in households. Regulation No. 245/2009 applies to fluorescent and high intensity discharge (HID) lamps and their ballasts and luminaires, which are typically used in the tertiary sector including outdoor lighting. As a consequence of this regulation, the high pressure mercury lamps and retrofit high pressure sodium lamps which are commonly used in road lighting will be banned from 13 April 2015. Additionally, the efficacy and performance requirements are given for high pressure sodium lamps and metal halide lamps. The estimated annual energy savings resulting from these regulations in the lighting sector in the EU are 75 TWh by 2020.

Road lighting design guidelines and photometric requirements in Finland are provided by the Finnish Transport Agency [**10**]. The recommendations are based on the European standards EN 13201:2-4 [**11**] - [**13**]. The recommendation and the standard EN 13201:2 give values for average road surface luminance (L_{ave}), overall luminance uniformity (U_o), and longitudinal luminance uniformity (U_l), the threshold increment (*TI*) and the surround ratio (*SR*). According to the Finnish road lighting recommendations, the average road surface luminance varies between 0.5 cd/m^2 and 2 cd/m^2. These recommendations are based on photopic photometry [**14**].

The luminance of any point on the road surface is a function of the illuminance on the road and the reflection characteristics of the road surface. Road surface reflection properties depend on the nature and physical state of the surface [**15**]. The pavement reflection characteristics depend on the aggregate type, colour and lightness, binding material, texture of the surface, and method of construction of the surface. Additionally, the reflection properties change as a result of wear and different weather conditions. The reflection properties of the pavement material are expressed as a table of reduced luminance coefficients called the *r*-table. Road lighting design is based on the standard *r*-tables defined by the International Commission on Illumination (CIE) [**15**]. However, these tables are based on measurements made in the 1960s and 1970s [**16**], [**17**] and new pavement materials have been introduced since then. The pavement materials commonly used today are dark [**18**], [**19**], and thus more light is needed to achieve the same luminance levels on the road surface as with the pavement materials used before.

The basis of all photometry is the photopic spectral luminous efficiency function *V(λ)* defined by the CIE in 1924 [**14**]. It is based on photopic vision which takes place at high ambient light levels, e.g. during the daytime. Scotopic vision is related to vision at very low light levels. It is represented by the scotopic spectral luminous efficiency function *V'(λ)*, introduced by the CIE in 1951 [**20**]. Mesopic vision relates to lighting levels between photopic and scotopic vision. The mesopic spectral sensitivity is not constant. It shifts from photopic to scotopic with decreasing light levels. The mesopic spectral sensitivity was defined by the CIE in 2010 [**21**]. The new CIE mesopic photometric system is valid between 0.005 cd/m^2 and 5 cd/m^2. Thus, road lighting recommendations fall within the mesopic region.

The reduction of energy consumption is one of the main goals in the EU. As road lighting is a major consumer of electrical energy, the potential for savings in road lighting practices is a motivation for this work. The current development of light sources and the Ecodesign Directive as well as the CIE recommended system for mesopic photometry, are also changing road lighting practices, and thus they fall within the scope of this thesis.

1.2 Aim of the work and research methods

The overall aim of this thesis was to investigate the effect of pavement reflection characteristics and mesopic dimensioning on the performance of road lighting. The first objective was to investigate the present state of the reflection properties of the pavement types used on Finnish roads. Pavement samples of various types and ages were collected from Finnish roads and their refection properties were measured and analysed. The second objective was to analyse the spectral reflectance of differently coloured pavement materials and of different types of new pavement materials. Pavement samples were measured to study the effect of pavement colour and lightness on the spectral reflectance properties of the pavements. Pavement samples were also manufactured from various experimental materials and their reflection properties were measured and their performance analysed. The third objective was to investigate the effects of the new CIE system for mesopic photometry on road lighting performance.

1.3 Scope of the work

The overall performance of road lighting is a combination of several factors, such as the energy consumption of luminaires, luminaire reflection properties, luminaire light source properties, ballasts, luminaire optics, luminaire placing, intelligent road lighting control systems, pavement reflection properties, appropriate photometric dimensioning of the lighting system, different weather conditions and vehicle headlights. This thesis investigates the effect of pavement reflection properties and mesopic dimensioning on road lighting performance. Tunnel lighting is excluded from this thesis.

2 State of the art

2.1 Road lighting performance and design

Road lighting was first introduced to reduce high crime rates [**22**], [**23**]. Today, the purpose of road lighting is to increase the safety of road users. The purpose of road lighting is to make people, vehicles, and objects on the road visible without causing discomfort to the driver at as low a cost as possible [**24**]. The driver's performance is also influenced by the road lighting: increasing the average luminance level reduces the risk of accident, and hence, lengthens the sight distance, improves visual perception, and shortens the reaction time [**25**], [**26**].

Luminance has traditionally been the basic quantity that determines the quality of road lighting [**27**] - [**29**]. The first recommendation given by the CIE concerning road lighting is given in publication No. 12, "International Recommendations for the Lighting of Public Thoroughfares" [**30**], published in 1965. The publication was revised in 1977 in CIE publication No. 12.2. "Recommendations for the Lighting of Roads for Motorised Traffic" [**28**]. This report was further updated in 1995 [**31**] and later in 2010 [**32**] to add recommendations for the lighting of conflict areas and roads frequented used by pedestrians and other users.

Road lighting design and calculation in Europe are based on the Technical Report EN 13201:1 [**33**] and the European Standard EN 13201:2-4 [**11**] - [**13**]. The technical report specifies the lighting classes set out in the standard and it gives guidelines for the application of these classes. The standard gives values for the average road surface luminance L_{ave}, overall luminance uniformity U_o, longitudinal luminance uniformity U_l, loss of visibility caused by disability glare (Threshold Increment *TI*), and light of the surroundings (Surround Ratio *SR*).

Guidelines for road lighting energy efficiency have been given by Boyce et al [**34**] and Kostic et al [**35**]. Boyce examined how the technology used, control systems, standards and recommendations, and lighting design could be changed while minimising the energy consumption. According to Boyce et al [**34**], energy savings could be achieved by dimming or switching off lighting permanently and using remote monitoring systems and more efficient light sources, control gear, and luminaires. Boyce et al also stated that changes to standards should be considered as the principles of road lighting have changed little over many decades, while, for example, vehicle head lighting has changed enormously. Kostic et al [**35**] follow the same trend with a few additions. According to Kostic et al, proper design and the right determination of a street lighting class and a correct maintenance factor value should be established for the reconstruction of lighting and for new installations. Additionally, the reflection properties of the road surface should be measured. Kostic et al [**35**] also point out recommendations resulting from user needs: white light sources with proper colour rendering and safety issues are also important.

2.2 Pavement materials and reflection properties

The pavement reflection characteristics depend on the aggregate type, colour and lightness, binding material, texture of the surface, and method of construction of the surface [**15**]. Each point on a road has unique reflection characteristics, which change over time as different parts of the road wear differently. A classification system for road surface reflection properties was first introduced by the CIE in 1976 in publication No. 30, “Calculation and measurement of luminance and illuminance in road lighting” [**36**]. The reflection tables (*r*-tables) describe the reflection properties in the form of reduced luminance coefficients. The description parameters adopted by the CIE, the average luminance coefficient Q_o and the specular factors *S1* and *S2*, are slightly modified from Erbay’s system [**37**]. Erbay proposed the luminance coefficient for describing the lightness of the road surface and two factors for describing the specular properties of dry road surfaces. The luminance coefficient proposed by Erbay was for vertical light incidence. The CIE changed the luminance coefficient proposed by Erbay to the average luminance coefficient Q_o proposed by de Boer and Westermann [**38**]. The specular factors proposed by Erbay were renamed *S1* and *S2* and the definition of *S2* was slightly changed. The average luminance coefficient Q_o can be calculated from the *r*-table using a weighting factor given by Sorensen [**39**]. The specular factor *S2* has been dropped from the CIE classification system as the specular factors *S1* and *S2* are highly correlated [**16**], [**17**]. This classification system of pavement reflection characteristics is still in use today.

Road surfaces are classified into classes according to their *S1* value. In 1976 [**27**] the CIE recommended the use of two sets of standard reflection tables, the R system (R1 - R4) and the N system (N1 - N4). The N system was intended for diffuse road surfaces where artificial brighteners were used. Burghout [**40**] demonstrated that combining the classes R2, R3, and R4 would make little difference to the predicted luminance patterns and recommended the use of a two-class classification system for road surfaces. As a result, the CIE added the C system (C1 - C2) in the road surface classification system in 1984 [**15**]. For wet surfaces the W (W1 - W4) classes are in use and the classification is made according to a modified parameter, *S1'*. The *r*-tables for wet conditions were published by the CIE in publication No. 47, "Road lighting for wet conditions", in 1979 [**41**]. Classification systems (R, N, C) for dry surfaces given in CIE publication No. 66 [**15**] and the classification system (W) for wet conditions given in CIE publication No. 47 [**41**] are in use today.

The road surface classification system is based on measurements made in the 1960s and 1970s [**16**], [**17**], [**42**]. New pavement materials have been introduced since then, and several studies [**18**], [**19**], [**43**], [**44**] indicate that the standard *r*-tables overestimate the reflection properties of today's pavement materials. Dumond et al [**19**] investigated very thin asphalt concrete (VTAC) and surface dressings (SD) in several different locations during a 36-month period. According to Dumont et al, VTAC is highly specular when the surface is new but the specularity decreases rapidly as a result of wearing. The average luminance coefficient of VTAC is also lower than the normalised value for the appropriate road class. For the SD, both the specularity and the average luminance coefficient increase over time. The standard *r*-tables overestimate the diffuse lope (see Section 3.1.) and underestimate the specular lope (see Section 3.1.). According to Fotios et al [**18**], the new asphalt-based pavement and the new concrete-based pavement materials do not represent the reflection characteristics of the standard *r*-tables. The standard *r*-tables overestimate the average luminance coefficient of British pavement materials. Schreuder [**44**] investigated pavement materials in the Netherlands. The results of his investigation indicate that the drainage asphalt commonly used on Dutch highways does not fit the standard *r*-tables. The coarse dense asphalt that has been used for decades in the Netherlands still follows the standard *r*-tables used for road lighting design. Huijben et al [**43**] investigated closed asphalt concrete (DBA), stone mastic asphalt (SMA), and very open asphalt concrete (ZOAB) in the Netherlands. The results of the DBA and SMA followed the standard Q_o values but the ZOAB resulted in lower average luminance coefficient values of than used in the design.

Road surface reflectance measurements were also made in Finland in the 1980s and 1990s [**45**] – [**47**]. In these studies the samples were cut from the road surface: from the wheel track, from between the wheel tracks, and the edge of the road. Some samples were also made and worn in the laboratory. According to these studies most surfaces belong to road classes R1 and R2, which are also used for road lighting design today.

2.3 Mesopic photometry

The photopic spectral luminous efficiency function *V(λ)* was introduced by the CIE in 1924 [**14**] and the *V(λ)* function was standardised in 2004 [**48**]. The scotopic spectral luminous efficiency function *V'(λ)* was introduced by the CIE in 1951 [**20**]. The *V(λ)* is at the upper end of the mesopic region and the *V'(λ)* is at the lower end of the mesopic region. Several models for mesopic photometry were proposed before the recommended system for mesopic photometry was introduced in 2010 by the CIE [**21**]. Many of the earlier models [**49**] - [**61**] were based on brightness matching experiments, where subjects match test stimuli to reference stimuli for equal brightness. The brightness matching models have some drawbacks. Additivity, a definition of photometry assumed by the CIE [**58**], [**62**], is a property where a given spectral radiant quantity (e.g. radiant flux, radiant intensity, radiance etc.) can be weighed with an appropriate spectral luminous efficiency function and then summed linearly across the spectrum to quantify the corresponding luminous quantity [**21**]. However, for monochromatic light sources which are used in brightness matching experiments, additivity is not preserved. Additionally, in practice brightness matching of adjacent surfaces as a visual task is less important than visual target detection and target recognition, which are used as the visual criteria in the visually-based performance-based mesopic models [**63**].

Several visual performance-based mesopic models have been introduced, such as those of Rea et al [**64**], the MOVE consortium [**65**], and Viikari [**66**]. These models are based on a linear combination of the photopic *V(λ)* and the scotopic *V'(λ)*. All these models are of the same form, although the parameter values and the luminance regions over which they apply are different. The X-model proposed by Rea et al [**64**] is based on studies by He et al [**67**], [**68**], with several simplifications. The luminance region over which the X-model applies is between 0.001 cd/m^2 and 0.6 cd/m^2. The MOVE model proposed by the MOVE consortium [**65**] is based on data of different visual experiments: achromatic detection thresholds [**69**], reaction times [**70**], and achromatic recognition thresholds [**71**]. In the MOVE model the transition between the mesopic and photopic regions occurs at about 10 cd/m^2 and the transition between the mesopic and scotopic regions occurs at about 0.01 cd/m^2. The upper luminance limit of the modified MOVE model is 5 cd/m^2 and the lower luminance limit is 0.005 cd/m^2 [**66**]. The difference between the MOVE model and modified

MOVE model is the upper and lower luminance region over which the models apply. The recommended system for mesopic photometry was published by the CIE in 2010 [**21**].

3 Analysis of road surface performance

Road lighting recommendations are based on average luminance and luminance uniformities on the road surface. The luminance of any point of the road surface is a function of the illuminance and the reflection characteristics of the road surface. The reflection characteristics of the road surface depend on the nature and physical state of the pavement [**15**]. When the surface is wet or moist the specular reflection increases, resulting in greater luminance non-uniformity [**16**].

The pavement reflection characteristics depend on the aggregate type, colour and lightness, binding material, texture of the surface, and method of construction of the surface. The aggregate colour and lightness are heavily dependent on the regional availability of the material and aggregate quality requirements in different countries. Road surface reflection properties change as a result of wearing and different parts of the road wear differently.

Road surface reflection characteristics are characterised by the average luminance coefficient Q_0, specular factors $S1$ and $S2$ and the table of reduced luminance coefficients (*r*-table). Each road surface has a unique *r*-table. In a system defined by the CIE [**15**] road surfaces are classified into classes according to the value of the specular factor $S1$, which is assumed to be representative of the reflection properties of the respective class. All these classes are generalisations of various pavement materials that have similar reflection characteristics.

3.1 Road surface reflection indicatrix and *r*-tables

Road surface reflection properties are given in a reduced luminance coefficient table, the *r*-table, where the luminance coefficients q are given as a combination of the angles β and $\tan\gamma$. The luminance coefficient depends on angles the α, β, δ and γ (Figure 1a) The angle of observation α is held constant at 1° for the standardised viewing height 1.5 m [**12**], [**15**] and for the area of the road between 60 m and 160 m ahead of the driver, which is considered an important area for the detection of obstacles [**26**]. The angle

δ between the plane of observation and road axis can usually be neglected, since this angle is never greater than 20° for road widths up to 25 m and observation distances greater than 60 m [**26**]. Thus, the luminance coefficient is dependent on the angle between the plane of light incidence and the plane of observation ($0° \leq \beta \leq 180°$), and the angle of light incidence ($0° \leq \gamma \leq 90°$). The reflection indicatrix shown in Figure 1b indicates the q-values as a function of the angles β and γ. The reflection indicatrix consists of a diffuse lobe and a specular lobe. The diffuse lobe is centred around the normal of the surface and the specular lobe is centred around the specular direction. Figure 1b also shows the range of angles β and γ upon which the r-table measurements are made. The shape of the reflection indicatrix characterises the degree of specularity ($S1$ value), and the volume of the indicatrix the degree of lightness (Q_o value).

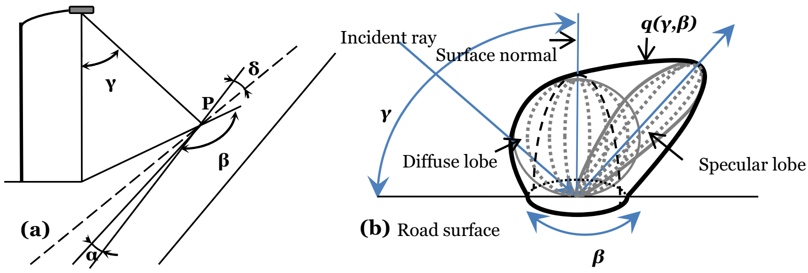


Figure 1. a) Angles α (angle of observation), β (angle between the plane of light incidence and the plane of observation), γ (angle of the light incidence), and δ (angle between the plane of observation and the road axis) upon which the luminance coefficient q of a road surface is dependent at the point of interest P [**26**]. b) Reflection indicatrix $q(\gamma, \beta)$ showing the specular lobe and the diffuse lobe of the reflection.

3.2 Road surface reflection properties

The standard r-tables are based on the pavement materials and measurements made in the 1960s and 1970s [**16**], [**17**], [**44**]. New pavement materials have been introduced since then. Economic, environmental, and wear resistance aspects have affected the development of new pavement materials [**72**]. The aggregate used for the pavement material is dependent on the quality requirements in different countries. In Finland the pavement materials and their quality requirements are defined by PANK ry, which coordinates the road construction industry [**72**]. The pavement quality requirements [**73**] are based on the European standards and Finnish weather and wearing conditions. The pavement materials commonly used today are darker and standard r-tables are no longer representative of their reflection properties [**18**], [**19**], [**43**], [**44**].

The purpose of this work was to investigate the reflection characteristics of the pavement materials currently used on Finnish roads and how they compare to the standard reflection tables given by the CIE. The research was carried out by extracting different types of pavement samples from roads. The *r*-tables of the samples were measured and the results were compared to the standard *r*-tables.

3.2.1 Experimental set-up

Pavement samples were extracted from nine different locations in southern Finland. The roads where the samples were extracted varied from country roads with a low traffic density to urban roads that carry heavy traffic. The samples were of different pavement types, typically used on Finnish roads. Asphalt concrete (AB), stone mastic asphalt (SMA), and Hilja noise-reducing quiet asphalt are mainly used on roads carrying heavy traffic. Soft asphalt (PAB-V) is used on low-traffic roads. Two samples were taken from each road: from the wheel track and between the wheel tracks. One sample was also taken from the verge of the road. The pavement samples were mostly from roads paved two years ago. Table 1 lists all the pavement (Figure 2) samples, their age and type, and the average daily traffic (ADT) of the road, and some of the samples are presented in Figure 2.

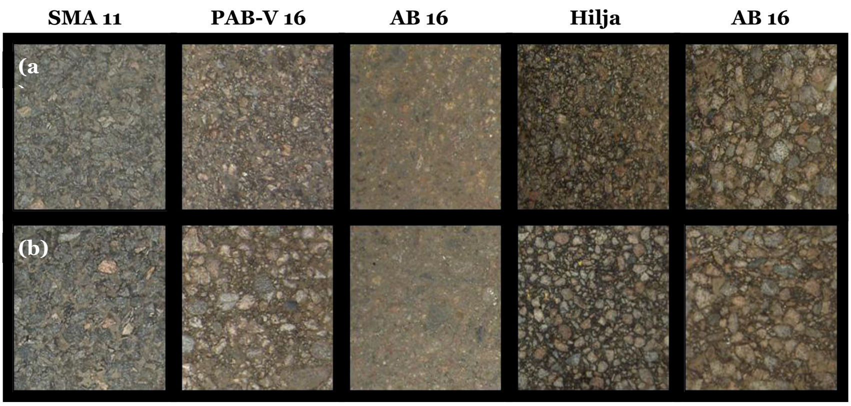


Figure 2. On the top row (a) are presented samples taken from between the wheel track and on the bottom row (b) are samples taken from the wheel track. Pavement samples from left to right: sample 6 (SMA 11), sample 3 (PAB-V 16), sample 8 (AB 16), sample 7 (Hilja), and sample 9 (AB 16). [II]

Table 1. Pavement samples. Average daily traffic (ADT) of the road, pavement type, pavements' wearing time (age) and place of extraction of the sample. [II]

Sample ID	Pavement Type	ADT [number of vehicles/24h]	Age [a]	Location
1	PAB-V 16	121	2	Kirkkonummi
2	PAB-V 16	229	2	Kirkkonummi
3	PAB-V 16	77	2	Hyvinkää
4	PAB-V 16	271	2	Lapinjärvi (only wheel track)
5	SMA 11	9255	3	Helsinki
6	SMA 11	2900	5	Espoo
7	Hilja	6489	1	Espoo
8	AB 16	2931	2	Espoo
9	AB 16	1959	2	Espoo
10	SMA 16	1959	2	Espoo (only verge of the road)

The reflection tables were measured in a laboratory with a gonioreflectometer (Figure 3b). The measurements were performed according to the method described in CIE Publication No. 30-2 [**29**]. The measurement set-up consists of a fixed table, where the pavement sample is set (see Figure 3a). A metal halide lamp (Philips Master SDW-T 100W/825) is set at a constant distance from the sample and it is moved over an arc about the sample to obtain the combinations of the angles β and γ (see Section 3.1, Figure 3c). CIE publication No. 30-2 recommends the use of an incandescent lamp with a high colour temperature for measuring most of the surfaces and for deeply coloured surfaces the influence of differently coloured light sources should be tested separately [**29**]. An image of the filament of the incandescent light bulb is, however, formed in the measuring field of the sample and therefore a metal halide lamp is used for the measurements [**74**]. The light source is at the bottom of a 3-m-long arm in a case, the purpose of which is to eliminate ambient light. A lens gathers up the light towards the top of the arm, where a mirror reflects it to the centre of the pavement sample. Thus, the total length of the light source from the pavement sample is 5 m. A Prichard 1980A spot luminance meter is fixated on the pavement sample at the observation angle of 1°. A relative calibration method was used with a reference surface of ρ = 0.97. In a relative calibration method a diffuse surface with a known reflection coefficient ρ is set perpendicular to the angle of light incidence and the luminance L_o of the reference surface is measured. The luminance coefficient q for the corresponding luminance L and angle γ is then equal to

$$q = \frac{\rho L}{\pi L_0 \cos \gamma} \qquad [1]$$

The accuracy of the Prichard 1980A luminance meter is ± 4% [75]. The accuracy of the total reflection measurement, including the luminance meter and the gonioreflectometer, is 5-15% depending on the roughness of the pavement sample [74]. The inaccuracy is caused by the setting up of the pavement sample and the luminance meter, the pavement sample and the luminance meter themselves, turning the arm to obtain the angles β and γ, the light source, and the calibration method.

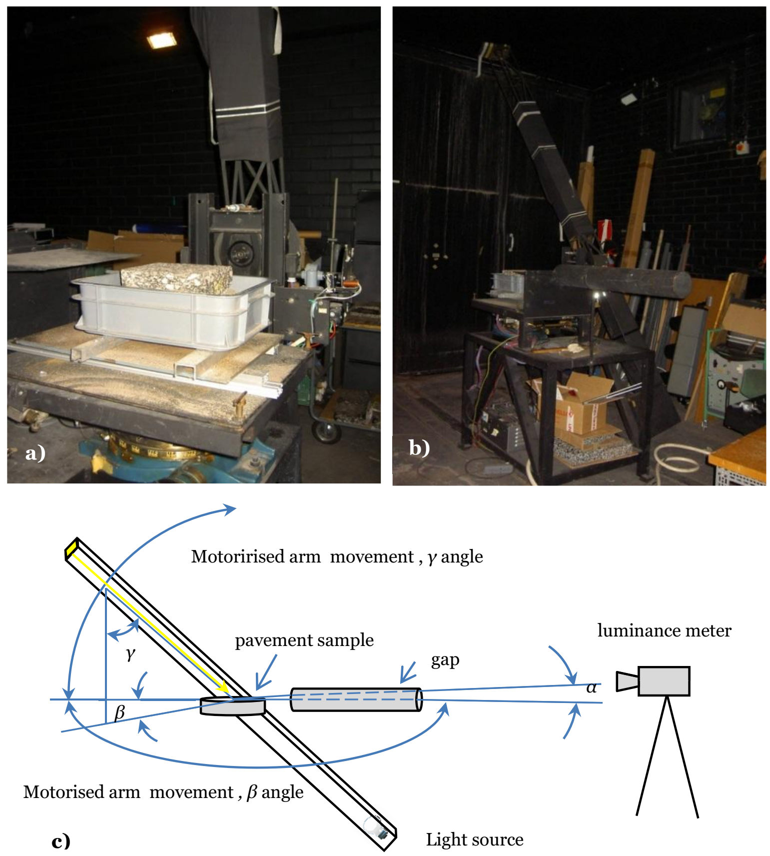


Figure 3. In the surface reflection measurement system a) the pavement sample is placed on a fixed table b) and the luminance is measured through a gap. A motorised arm with a light source c) is moved over an arc to obtain the different combinations of β and γ.

3.2.2 Results of road surface reflection measurements

The *r*-tables were measured for each pavement sample. The average luminance coefficient Q_o, and specular factors $S1$ and $S2$ are calculated from the *r*-tables for each sample. These results and an average value for the two samples taken from the same road are shown in Table 2.

Table 2. Calculated values for Q_o, $S1$, and $S2$ for the samples taken from the wheel track and between the wheel tracks. The average of Q_o, $S1$, and $S2$ is the average value for the two samples taken from the same road (wheel track value and the value between the wheel tracks). A road class is assigned to each sample according to its $S1$ value. [II]

Sample ID	Wheel track				Between wheel tracks				Average			
	Average luminance coefficient Q_o	Specular factor $S1$	Specular factor $S2$	standard r-table class	Average luminance coefficient Q_o	Specular factor $S1$	Specular factor $S2$	standard r-table class	Average luminance coefficient Q_o	Specular factor $S1$	Specular factor $S2$	standard r-table class
1	0.05	0.22	1.35	R1	0.09	0.19	1.61	R1	0.07	0.20	1.48	R1
2	0.08	0.28	1.57	R1	0.05	0.27	1.34	R1	0.07	0.27	1.45	R1
3	0.08	0.25	1.33	R1	0.08	0.30	1.42	R1	0.08	0.28	1.38	R1
4	0.08	0.34	1.48	R1								
5	0.07	0.29	1.46	R1	0.07	0.26	1.40	R1	0.07	0.28	1.43	R1
6	0.07	0.43	1.61	R2	0.07	0.35	1.60	R1	0.07	0.39	1.61	R1
7	0.09	0.24	1.25	R1	0.04	0.15	1.55	R1	0.06	0.20	1.40	R1
8	0.09	0.18	1.18	R1	0.07	0.22	1.46	R1	0.08	0.20	1.32	R1
9	0.09	0.20	1.30	R1	0.08	0.29	1.67	R1	0.09	0.25	1.48	R1
10	0.06	0.68	1.97	R2								

The average values calculated from the wheel track and between the wheel tracks classify all the samples to road class R1. The normalised values for road class R1 are $Q_o = 0.10$ and $S1 = 0.25$. Almost all the samples have an $S1$ value close to the normalised value. The average luminance coefficient Q_o value is lower than the normalised value. Thus, the samples are darker than the standard R1 pavement.

The average luminance coefficient Q_o value and the specular factors $S1$ and $S2$ give numerical values of the reflection properties of the pavement. The shape of the reflection is given in the form of a reflection indicatrix. The measured reflection tables are presented in two-dimensional reflection indicatrices; see Figures 4 - 7. The reflection indicatrix presents the *r*-table $r(\beta, \tan\gamma)$ projected to *z*-plane in spherical coordinates where $x = r(\beta, \tan\gamma)\sin\gamma\cos\beta$, $y = r(\beta, \tan\gamma)\sin\gamma\sin\beta$ and $z = r(\beta, \tan\gamma)\cos\gamma = 0$.

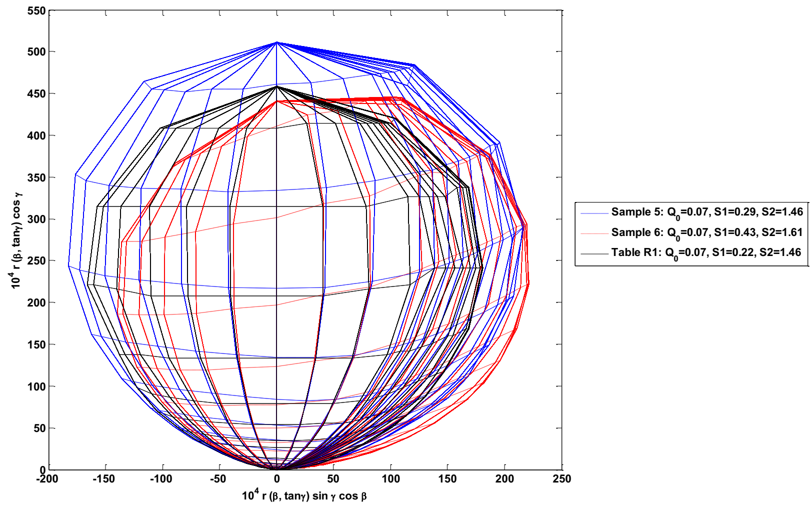


Figure 4. Sample 5 (Q_o = 0.07, $S1$ = 0.29) and sample 6 (Q_o = 0.07, $S1$ = 0.43) taken from the wheel track. Standard *r*-table R1 is rescaled according to Q_o = 0.07. [II]

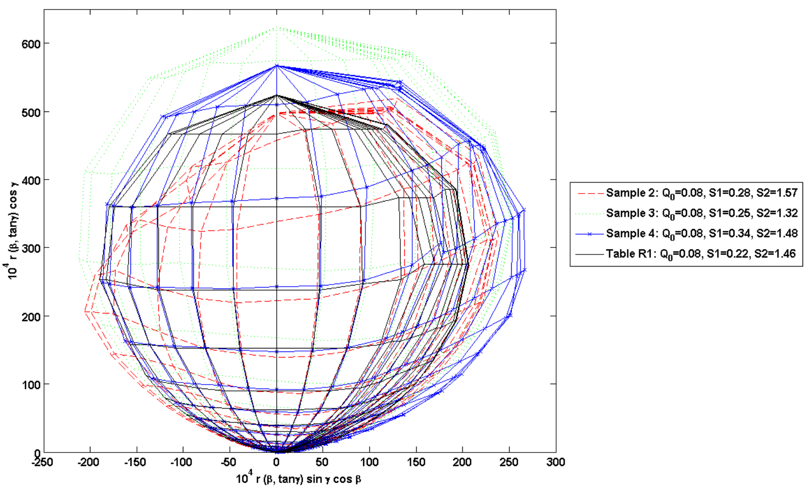


Figure 5. Sample 2 (Q_o = 0.08, $S1$ = 0.28), sample 3 (Q_o = 0.08, $S1$ = 0.25), and sample 4 (Q_o = 0.08, $S1$ = 0.34) taken from the wheel track. Standard *r*-table R1 is rescaled according to Q_o = 0.08. [II]

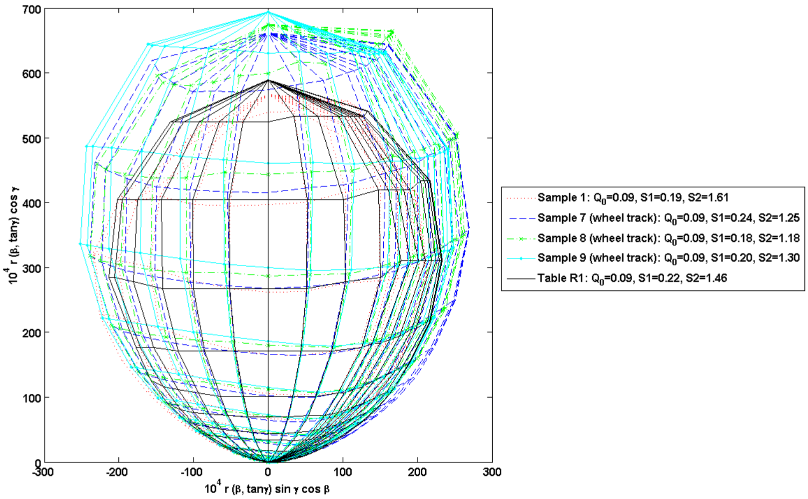


Figure 6. Sample 1 (Q_o = 0.09, $S1$ = 0.19) taken between the wheel tracks and sample 7 (Q_o = 0.09, $S1$ = 0.24), sample 8 (Q_o = 0.09, $S1$ = 0.18), and sample 9 (Q_o = 0.09, $S1$ = 0.20) taken from the wheel track. Standard *r*-table R1 is rescaled according to Q_o = 0.09. [II]

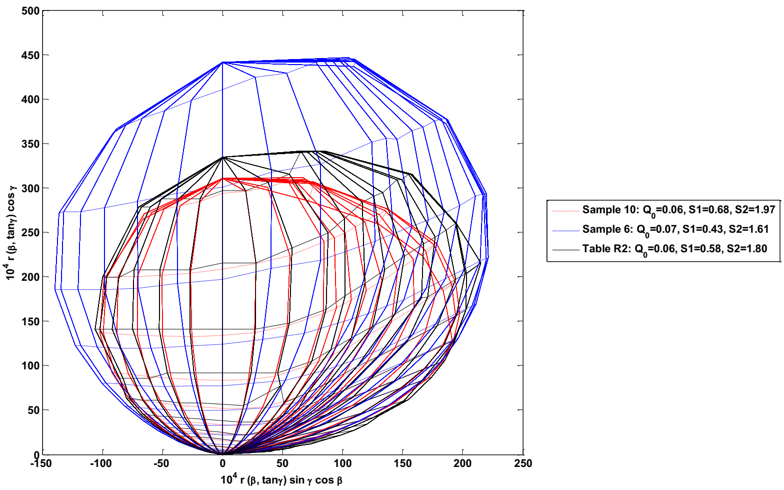


Figure 7. Sample 6 (Q_o = 0.07, $S1$ = 0.4) taken from the wheel track and sample 10 (Q_o = 0.06, $S1$ = 0.68) taken from the verge of the road. Standard *r*-table R2 is rescaled according to Q_o = 0.06. [II]

The shape of the reflection indicatrices for samples PAB-V, SMA, and AB represent reflection tables R1 and R2 to a large degree, but not for the Hilja noise-reducing pavement. Rescaling the standard *r*-tables to match the Q_o value of the measurements (PAB-V, SMA, and AB) does not produce a good fit between these reflection indcatrices [II]. Most of the differences occur at small beta angles. Thus, they are more specular than the standard *r*-tables. There are also some differences at large beta angles. Hence, standard *r*-tables underestimate the diffuse reflection [II].

The volume contained within the indicatrix represents the level of total reflectivity and the shape characterises the degree of specularity [**15**]. The volume of the indicatrix is the same at the same Q_o value. According to these measurements, in most cases the standard *r*-table appears to be enclosed inside the measured indicatrices. The standard *r*-table seems to overestimate the reflection for high angles of incidence and underestimate the reflection for low angles of incidence. The Hilja noise-reducing pavement material has a unique reflection indicatrix and the standard reflection table for R1 class overestimates its specular reflection and underestimates its diffuse reflection [II].

The observed pavement materials are diffuse and somewhat dark. The average specularity value $S1$ of all the samples except sample 6 is close to the standard value (0.25) for road class R1. The average luminance coefficient Q_o of all the samples, on the other hand, is lower than the normalised value (0.10) for road class R1. The Q_o value is closer to the normalised Q_o value for road classes R2 (0.07), R3 (0.07), and R4 (0.08). The standard *r*-table (R1) reflection indicatrix does not give an adequate fit for the degree of lightness [II].

The standard *r*-table (R1) reflection indicatrix gives an adequate fit for the degree of specularity. However, the specular lobe and the diffuse lobe of the reflection of the measured road surface samples are overrated compared to the rescaled standard *r*-table. Also, for low angles of incidence, the reflection of the measured pavement samples is overrated and for high angles of incidence the reflection is underrated compared to the rescaled *r*-table.

3.3 Pavement colour and lightness

The reflectance properties of road surfaces depend on the nature of the pavement material [I]. Pavement materials vary in their surface composition, texture, method of construction and the aggregate type used, aggregate colour, and aggregate lightness. The aggregate used, on the other hand, is heavily dependent on the regional availability of the aggregate and aggregate quality requirements in different countries.

The CIE standard publication No. 30-2 recommends incandescent lamps with a high colour temperature to be used for measuring the reflectance characteristics of most of the road surface samples [**29**]. For deeply coloured road surfaces the influence of various light sources with a different light spectrum should be tested separately. Road lighting design is usually performed with standard *r*-tables and Q_o values regardless of the light sources installed on the street and the pavement materials used on the road surface. Thus, road lighting installations may result in significantly different road surface luminance values compared to the designed values.

The purpose of this study was to investigate the effect of pavement type, pavement lightness, and pavement colour on the spectral reflectance properties of the pavement. The study was carried out by measuring the spectral reflectance of dry and wet pavement samples under metal halide and high pressure sodium lamp illumination.

3.3.1 Experimental set-up

The measurements were performed on seventeen samples of varying pavement types and aggregate colour. The samples were mostly stone mastic asphalt (SMA) pavement of varying aggregate grading, aggregate type, and pavement composition. The Prall [**76**] method was used for the wearing of the samples.

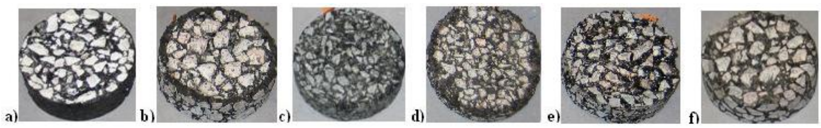


Figure 8. Six different pavement samples used in the measurements: a) SMA 16 W1 with white aggregate; b) SMA 18 L2 with light slightly reddish aggregate; c) SMA 8 G1 quiet asphalt sample with dark greyish aggregate; d) SMA 8 Q2 Hilja noise-reducing quiet asphalt; e) SMA 11 A; f) SMA 16. [I]

The measurements were made using a CS-2000 spectroradiometer (accuracy ± 2%). The measurement angle was set to α = 35° (see Figure 1). The measurements were made under an Osram HCI-TS 70-W/942 NDL metal halide (MH) lamp and an Osram NAV-TS Super 70-W (SON-TS Plus) high pressure sodium (HPS) lamp. The relative spectral power distribution of the light sources is shown in Figure 9. A white barium sulphate surface (ρ = 0.97) was used as a reference. The angle between the vertical plane of incidence and vertical plane of observation was set to β = 20° (see Figure 1). The angle of incidence from the upward vertical was set to γ = 35° (see Figure 1). Some of the samples were also measured with different angles of β (90°, 55°, 35°, 25°, 20°, 13°) and γ (50°, 46°, 40°, 35°, 30°, 25°, 20°, 13°). Wet pavement samples were also measured to study the changes in reflection properties compared to dry ones.

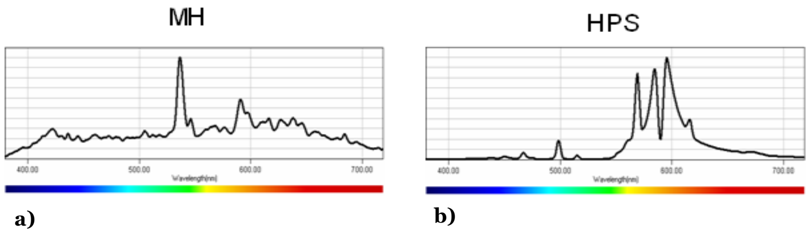


Figure 9. Relative spectral power distributions of a) Osram HCI-TS 70-W/942 NDL metal halide (MH) lamp and b) Osram NAV-TS Super 70-W (SON-TS Plus) high pressure sodium (HPS) lamp.

3.3.2 Results

The relative spectral reflectances were measured for all the samples; see Figures 10 – 11. The relative reflectances were higher in the long wavelength region for most of the samples [I]. The results indicate that light sources with high output in the long wavelength region are more effective in terms of light reflected from the pavements compared to the ones with high output in the short wavelength region [I].

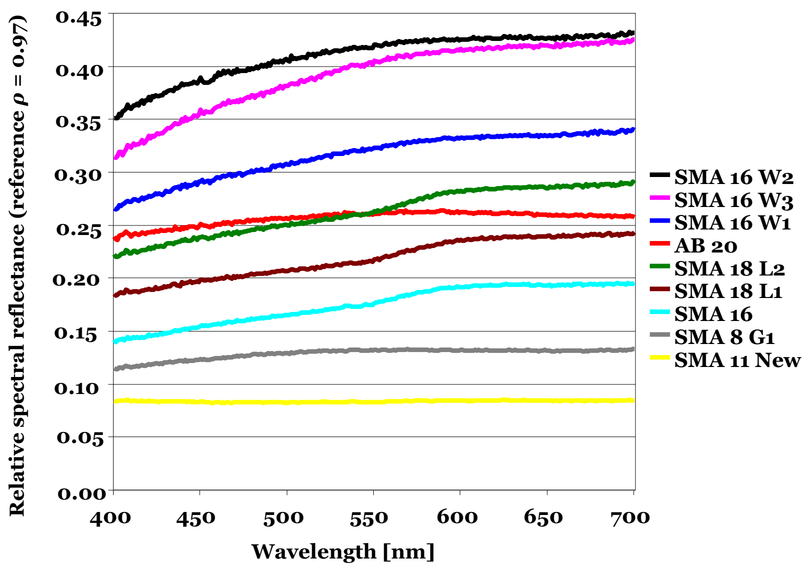


Figure 10. Relative spectral reflectances of nine different pavement samples measured under the MH lamp spectrum (β = 20°, γ = 35°). A white barium sulphate surface (ρ = 0.97) with homogenous spectral reflectance was used as a reference. [I]

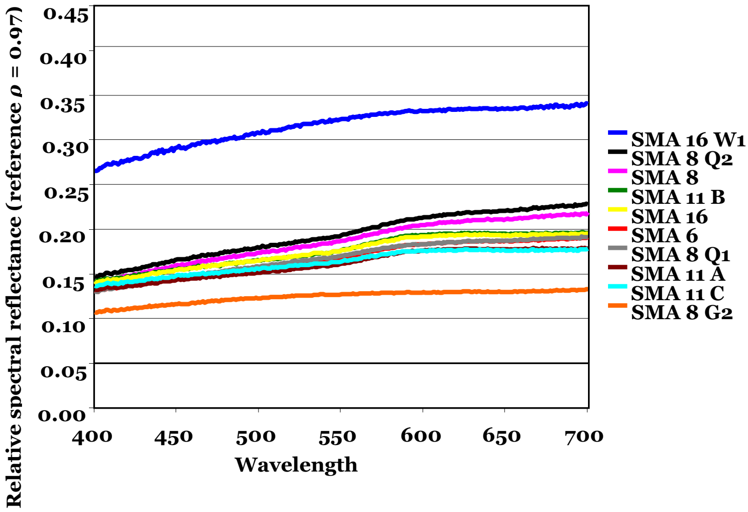


Figure 11. Relative spectral reflectances of ten different pavement samples measured under the MH lamp spectrum (β = 20°, γ = 35°). A white barium sulphate surface (ρ = 0.97) with homogenous spectral reflectance was used as a reference. [I]

Figure 12 shows the relative spectral reflectance of sample SMA 6 for various combinations of angles β and γ. The shape of the relative spectral reflectance curve remains almost the same with different angles of β and γ. The reflectance values and the total reflectances of the pavement samples, however, varied significantly, depending on the angles of β and γ.

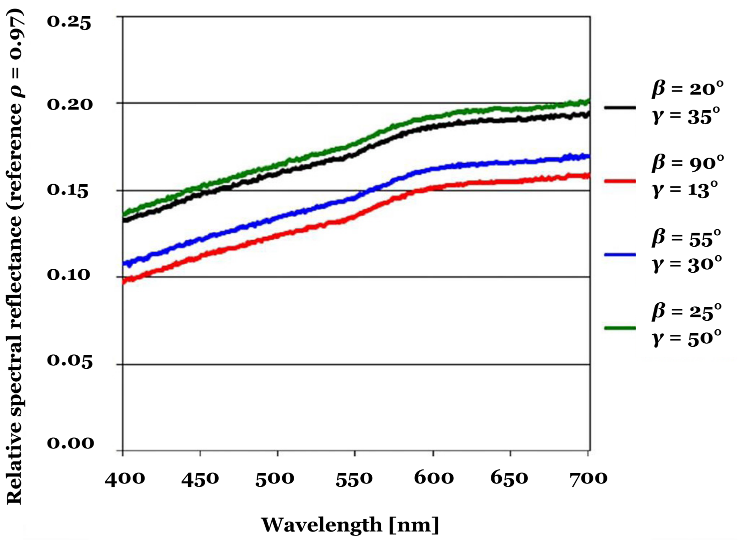


Figure 12. Relative spectral reflectances of SMA 6 sample measured with different angles of β and γ. A white barium sulphate surface (ρ = 0.97) with homogenous spectral reflectance was used as a reference. [I]

The relative spectral reflectances of three pavement samples (SMA 16 W1, SMA 16, and SMA 8 Q2) in dry and wet conditions were also measured. No significant differences were found in the shape of the spectral reflectance curves between the dry and wet pavement samples [I]. The spectral reflectance values for the wet samples were lower than those for the dry ones. The change in the reflectance values of the wet samples depends on the material of the pavement: the difference between the relative spectral reflectance in the dry and wet conditions is greater for darker samples. The results show that pavements which have higher reflectance in the long wavelength region still maintain the same feature when the pavement becomes wet.

Relative luminances were calculated for different pavement samples measured under an MH lamp and an HPS lamp (Figure 13). For most of the measured pavement samples the relative luminances were higher when illuminated with HPS lamps compared to the MH illumination [I]. The relative luminance of SMA 16 W1 is almost three times higher than the relative luminance of SMA 8 G1. Therefore, luminaires would have to produce three times more light to achieve the same luminance levels on the road if SMA 8 G1 pavement is used instead of SMA 16 W1 pavement [I].

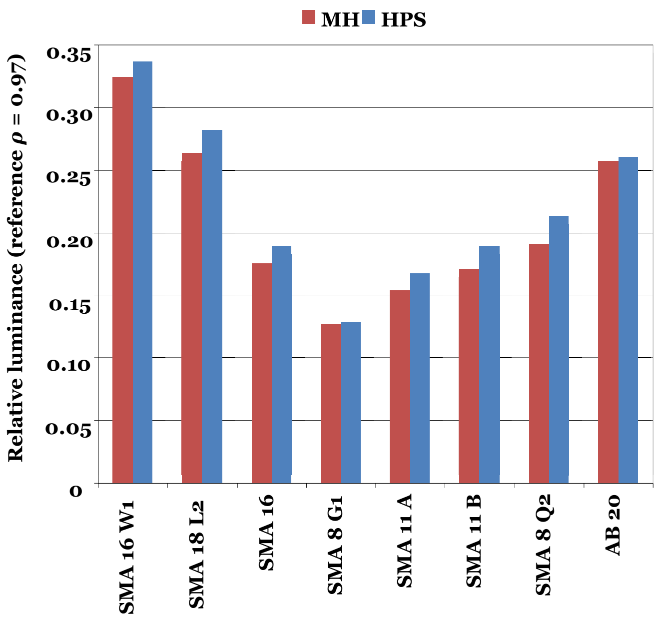


Figure 13. Relative luminances of eight different pavement samples. Relative luminances were measured under metal halide (MH) and high pressure sodium (HPS) lamp lighting (β = 20°, γ = 35°). [I]

3.4 New pavement materials

The mechanical strength, skid resistance, and costs are relevant when choosing road surface materials. The asphalt mixtures used on roads are comprised of aggregate particles of various sizes, mineral filter, and a binding agent, which is typically bitumen. The colour of the asphalt pavement is dependent on the mixture type, colour of aggregate used in the mixture, service conditions, and time in service.

In recent years great effort have been made to increase the energy efficiency of road lighting and to limit the greenhouse gas emissions caused by road lighting. From the road lighting point of view the road surface is also a component of the lighting system, as the reflection characteristics of the surface material significantly influence the luminance obtainable with a given amount of luminous flux from the luminaires. Darker pavement materials need more radiant power from the luminaire than lighter pavement materials. Additionally, the environmental aspects and sustainable development by preserving and conserving natural resources and reducing waste are of growing interest in road construction. Recycled materials like industrial waste, construction waste, waste tyres, waste glass etc. preserve resources and reduce waste.

The purpose of the study was to develop and investigate alternative lighter pavement materials for pedestrian ways using local limestone aggregate and recycled materials. Pedestrian ways were chosen for cost and pavement quality requirement reasons. Pavement laid on a pedestrian way will not be exposed to wear by traffic and studs and, therefore, the quality requirements of the pavement are of less concern. The research was carried out by manufacturing several pavement slabs using different production methods and by varying the type and the amount of light-reflecting materials. The reflection properties of these samples were measured and the potential of the aggregates for pedestrian way lighting was studied.

3.4.1 Experimental set-up

The pavement samples were manufactured using regular asphalt pavements with surface coatings of three different raw materials: crushed limestone, crushed cement concrete, and crushed waste glass. The base mixture was asphalt concrete (AB) with a nominal aggregate size of 11 mm. The mixture was fabricated at the Aalto University Highway Laboratory using a 30-kg laboratory mixer and poured into a wooden box to prepare a slab for testing. The surface coating chips were sprinkled by hand on top of the slab and the slab was further compacted with a roller to obtain the required density for the mixture. One slab was used to obtain three different test samples. A total of five slabs were manufactured.

The chip size of the surface coating and the amount of the surface coating were varied. The reflection measurements were performed for each slab and then the slabs were worn by means of sand-blasting and then measured again. After the measurements the best materials from the lighting point of view were selected for further testing. Table 3 shows the materials used, chip sizes, and the amount of surface coating on each slab.

Table 3. Manufactured slabs and the use of chip materials and the amount of sprinklings (kg/m²). [III]

Slab ID	Chip materials	Chip size [mm]	Amount of surface coating [kg/m²]	Roller passes
1a	Crushed limestone, Solhem	1/8	1	1+9
1b	Crushed cement concrete			
1c	Crushed waste glass, Tasolasi			
2a,3a,4a	Crushed limestone, Solhem	0/11.2	2,3,4	1+9
2b,3b,4b	Crushed cement concrete	0/11.2	2,3,4	1+9
5a	Crushed limestone, Solhem	5.6/11.2	4	0+9
5b	Crushed limestone, Törmä			
5c	Crushed waste glass, Kirkas			

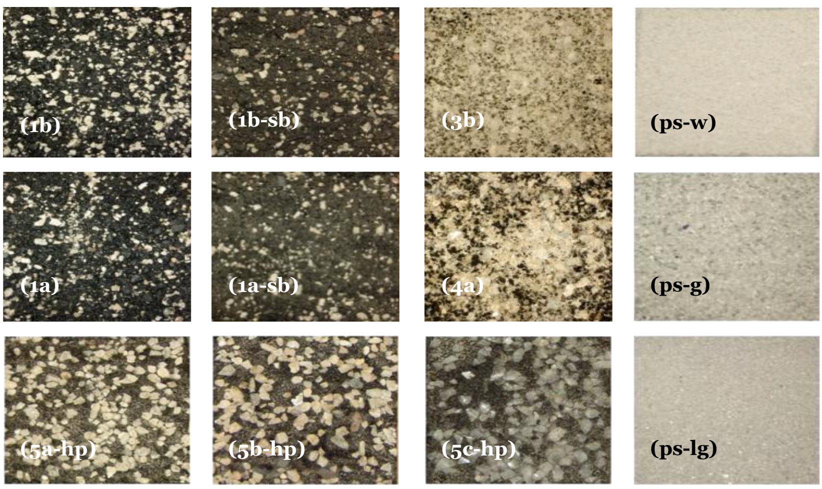


Figure 14. Manufactured pavement samples and factory-made paving stones. On the top row samples are presented: the crushed cement concrete samples 1b, 1b-sb, 3b, and the small white paving stone ps-w. In the middle row are limestone samples are presented: from the left 1a, 1a-sb, 4a and the large grey paving stone ps-g. On the bottom row, from the left, are samples 5a-sb (Solheim limestone), 5b-sb (Törmä limestone), 5c-sb (crushed waste glass), and the large light grey paving stone ps-lg.

The reflection characteristics of the samples were measured with a gonioreflectometer. A relative calibration method was used; see Section 3.2.1. For reference purposes, the reflection properties of three factory-made concrete paving stones were measured: a small white paving stone (ps-w), a large grey paving stone (ps-g) and a large light grey paving stone (ps-lg). Figure 14 shows some of the manufactured pavement samples and the factory-made paving stones.

3.4.2 Results

The reflection tables were measured for all the manufactured samples. Some of the samples were measured after they had been sand-blasted. Sand-blasting was used to simulate wearing. Sand-blasting is a severe wearing method and overestimates the wearing of pedestrian and bicycle ways.

Results of reflection measurements

The average luminance coefficient Q_o and the specular factors $S1$ and $S2$ were calculated from the measured reflection tables; see Table 4

The samples with waste glass (1c, 5c) are specular. The specularity decreases with wearing. The sample with coloured waste glass (1c) is also fairly dark. Wearing does not affect the lightness of the sample. The waste glass was the least usable material for pedestrian way lighting applications as a result of high specularity, lower lightness, and sharp glass chips, which are a risk for users.

A different amount of crushed cement concrete was used to study the effect on specularity and lightness (1b, 2b, 3b and 4b). Increasing the amount of concrete chips increases the lightness and reduces the specularity. There are, however, only minor differences in the Q_o value when the amount of concrete chips exceeds 2 kg/m^2. Sand-blasting wears most of the light concrete chips from the sample surface resulting in a somewhat uniform surface and the reflection properties of all the samples (1b, 2b, 3b, and 4b) are almost the same. Concrete chips would be suitable material from the pedestrian way lighting point of view, if the concrete chips could withstand wearing.

Two different limestones with different grading sizes and amounts were studied (1a, 2a, 3a, 4a, 5a, and 5b). Increasing the amount of limestone increases the lightness and reduces specularity. The fine limestone (1a, 2a, 3a, and 4a) does not form as uniform a surface as the crushed concrete chips (1b, 2b, 3b, and 4b). Sand-blasting wears the samples similarly and the Q_o, $S1$, and $S2$ values of the sanod-blasted limestone samples (1a, 2a, 3a, and 4a) are almost the same.

Table 4. Calculated Q_o, $S1$, and $S2$ values for the samples with no treatment, sand-blasted samples and, factory-made paving stones. [III]

Slab ID	Chip material at the top of the slab	Amount of surface coatings	Samples with no treatment			Sand-blasted samples		
			Average luminance coefficient	Specular factor	Specular factor	Average luminance coefficient	Specular factor	Specular factor
		[kg/m²]	Q_o	$S1$	$S2$	Q_o	$S1$	$S2$
1a	Crushed limestone, Solhem	1	0.07	1.05	2.29	0.07	0.46	1.74
2a	Crushed limestone chips	2	0.08	0.31	1.63	0.07	0.21	1.47
3a	Crushed limestone chips	3	0.10	0.25	1.85			
4a	Crushed limestone chips	4	0.10	0.16	1.46	0.07	0.19	1.44
1b	Crushed cement concrete	1	0.08	0.62	1.66	0.06	0.28	1.43
2b	Crushed cement concrete chips	2	0.10	0.18	1.47	0.05	0.26	1.87
3b	Crushed cement concrete chips	3	0.11	0.12	1.42			
4b	Crushed cement concrete chips	4	0.11	0.08	1.60			
1c	Crushed waste glass, Tasolasi	1	0.06	0.98	2.25	0.06	0.75	1.98
5c	Crushed waste glass, Kirkas lasi		0.11	1.38	3.80	0.12	0.48	1.98
5a	Crushed limestone, Solhem	4	0.09	0.36	1.47	0.11	0.13	1.11
5b	Crushed limestone, Törmä	4	0.10	0.40	1.70	0.14	0.12	1.34
ps-w	Small paving stone, white		0.19	0.30	1.43			
ps-g	Large paving stone, grey		0.17	0.14	1.29			
ps-lg	Large paving stone, light grey		0.18	0.12	1.27			

Factory-made concrete paving stones were measured as a reference; see Table 4. Their average luminance coefficients were significantly higher than those of any other manufactured and measured sample. The specular factor also classifies all the factory-made paving stones into road class R1. The samples were not worn as it is expected that these samples mostly darken with wearing.

Results of lighting calculations

Road and pedestrian way lighting calculations were made to study the energy consumption and annual costs per kilometre using the different pavement samples. The calculations were made for two different luminaires: a Philips Manta with a 150-W metal halide (MH) lamp and a Philips Manta with a 100-W high pressure sodium (HPS) lamp. The luminous intensity distribution curves of these luminaires are shown in Figure 15. The calculation set-up was a two-lane roadway with a width of 7 m and a pedestrian way with a width of 3 m that were adjacent to each other. The luminaires were set on 8-m-high poles 0.5 m from the edge of the pedestrian way. Luminaire spacing was optimized using the DIALux software [77] for lighting class ME3c (L_{ave} ≥ 1 cd/m², U_o ≥ 0.4, U_l ≥ 0.5, *TI* ≤ 15%, *SR* ≥ 0.5) for the roadway and S2 (E_{ave} ≥ 10 lx, E_{min} ≥ 3 lx) for the pedestrian way. The energy price was €0.1/kWh and the annual operating time 3900 hours. The results of the calculations are shown in Table 5.

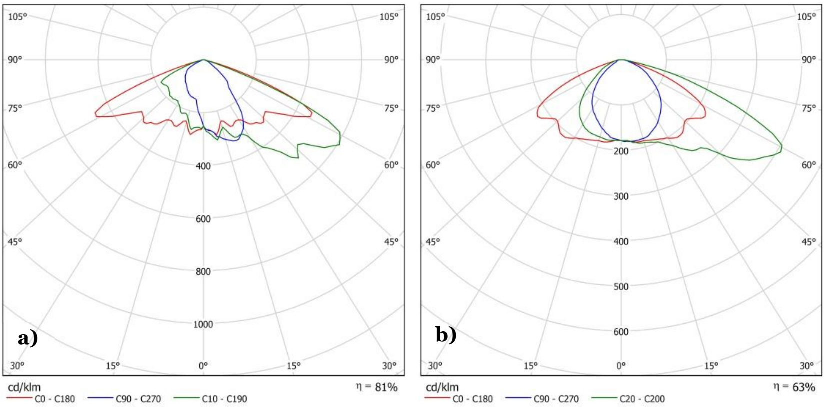


Figure 15. Luminous intensity distribution curves of a) Philips Manta 100 W HPS lamp luminaire b) Philips Manta 150 W MH lamp luminaire.

The calculations using the HPS lamp show that in all cases the annual energy costs per kilometre decrease as the Q_o value increases. For Q_o ≥ 0.1 the impact on the annual costs is not significant. The calculation results for the MH lamp installation show that the impact of the Q_o value on the annual energy costs of the street lighting installation behaves differently. The annual energy costs decrease as the Q_o value increases for Q_o < 0.09. For Q_o ≥ 0.09 the annual energy costs per kilometre increases.

The specular factor *S1* increases on average as the annual energy costs increase for the HPS lamp installation. For the ME lamp installation the specular factor *S1* behaves indeterminately. No specific pattern can be determined for the relationship of annual energy costs, luminance coefficient Q_o, and specular factor *S1*. The reason could lie in the shape of the reflection indicatrix. Figure 16 shows the reflection indicatrices of samples 2b, 4a, and 5a-sb. The annual energy costs are the highest for sample 5a-sb, which has higher reflection at high angles of β (β > 90°). The annual energy costs are the lowest for sample 2b, which has higher reflection at low angles of β (β < 90°). Sample 4a does not have higher reflection for high angles of β or low angles of β and the annual energy costs are in between those for samples 2b and 5a-sb. Thus, the specular lobe of the reflection indicatrices reduces the pole spacing and increases the annual energy costs.

Table 5. Calculation results for high pressure sodium lamp (HPS) installation and metal halide lamp (MH) installation of the optimised lantern spacing (*S*) for each pavement sample. The annual power consumption (*P*) of the installation is given in kilowatts per kilometre and the annual energy costs (cost) of the installation in euros per kilometre. The energy price used was €0.10/kWh. The sand-blasted samples are marked "sb" at the end of the samplen ame. [III]

Slap ID	Average luminance coefficient	Specular factor	HPS 100 W			MH 150 W		
			Luminaire pole spacing	Luminaire power consumption	Annual energy cost	Luminaire pole spacing	Luminaire power consumption	Annual energy cost
	Q_o	*S1*	*S* [m]	*P* [kW/km]	[€/km,a]	*S* [m]	*P* [kW/km]	[€/km,a]
1a	0.07	1.05	23	5.12	1995	33	4.38	1709
1a-sb	0.07	0.46	25	4.72	1839	32	4.52	1761
2a	0.08	0.31	26	4.54	1770	33	4.38	1709
2a-sb	0.07	0.21	21	5.59	2181	30	4.81	1875
3a	0.10	0.25	35	3.40	1326	31	4.66	1816
4a	0.10	0.16	36	3.31	1291	30	4.81	1875
4a-sb	0.07	0.19	22	5.34	2083	31	4.66	1816
1b	0.08	0.62	27	4.37	1706	36	4.03	1571
1b-sb	0.06	0.28	22	5.34	2083	32	4.52	1761
2b	0.10	0.18	35	3.40	1326	31	4.66	1816
2b-sb	0.05	0.26	14	8.33	3248	22	6.50	2536
3b	0.11	0.12	34	3.50	1364	28	5.14	2005
4b	0.11	0.08	32	3.71	1446	27	5.33	2077
1c	0.06	0.98	17	6.88	2683	26	5.52	2155
1c-sb	0.06	0.75	19	6.17	2405	29	4.97	1937
5a	0.09	0.36	32	3.71	1446	32	4.52	1761
5a-sb	0.11	0.13	33	3.60	1404	28	5.14	2005
5b	0.10	0.40	34	3.50	1364	31	4.66	1816
5b-sb	0.14	0.12	33	3.60	1404	28	5.14	2005
5c	0.11	1.38	22	5.34	2083	29	4.97	1937
5c-sb	0.12	0.48	36	3.31	1291	31	4.66	1816
ps-w	0.19	0.30	38	3.14	1225	31	4.66	1816
ps-g	0.17	0.14	34	3.50	1364	28	5.14	2005
ps-lg	0.18	0.12	35	3.40	1326	29	4.97	1937

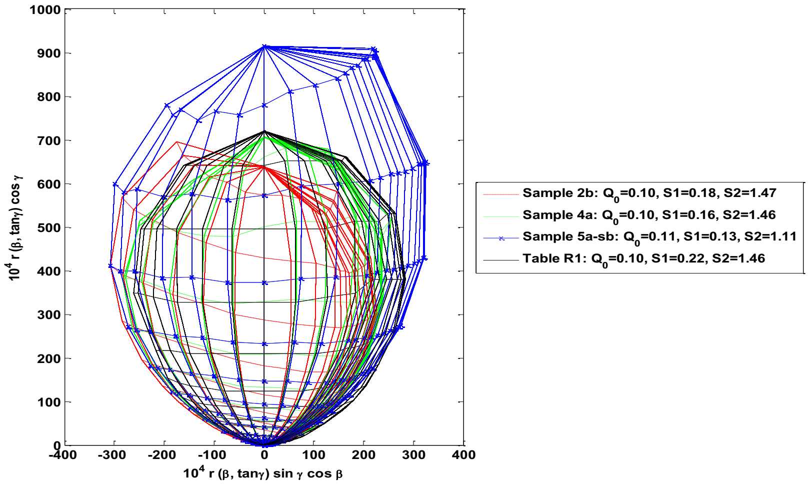


Figure 16. Reflection indicatrices of samples 2b, 4a, 5b-sb, and rescaled (Q_o = 0.1) reflection table R1.

The calculations using the HPS lamp show that the samples follow the annual energy costs calculated for the rescaled standard *r*-tables R1 and R2. The calculations for the MH lamp installation show that annual energy costs are higher using the measured *r*-tables of the pavement samples than using the rescaled *r*-tables R1 and R2. Additionally, the annual costs of the installation are the same for the scaled R1 pavement for $Q_o \geq 0.6$ and for the scaled R2 pavement for $Q_o \geq 0.7$.

The average road surface luminance increases as the Q_o value increases. The calculations indicate that longer spaces between lantern could be used to satisfy the road lighting photometric requirements (L_{ave}, U_o, U_l, *TI,* and *SR*) using pavement materials that have a higher Q_o value. However, increasing the lantern spacing affects the luminance uniformities. The impact in this case is greater in the MH lamp installation than in the HPS lamp installation. For the HPS lamp installation, the lantern spacing can be optimised to satisfy the photometric requirements without over-dimensioning the average road surface luminance. For the MH lamp installation, the average road surface luminance must be greater than the requirement for most of the samples if Q_o > 0.1 in order to satisfy the uniformity requirements.

The luminous intensity distribution of the luminaire also affects the luminance uniformities on the road surface. The luminous intensity distribution cure of the luminaire depends on e.g. the light source properties, luminaire optics and reflection properties, and ballasts. The β and γ angles where the luminous flux reaches maximum value, and the overall shape of the luminous intensity varies between different types of luminaires. In this case the HPS lamp luminaire distributes more light along the road surface and also across the road surface at higher angles of γ. Thus, the light distribution is more even over the road surface with the HPS lamp luminaire. The luminous intensity distribution of the MH lamp luminaire is more symmetrical at various angles of γ. Thus, the light distribution over the road surface is no as even as it is with the HPS lamp luminaire.

3.5 Synthetic light-coloured bitumen

Coloured pavements are used in tunnels, car park, parks, pedestrian ways, and other applications. Coloured pavements are a mixture of synthetic binders, pigment, aggregate, and filler of standard asphalt mixtures. The mechanical performance of synthetic binders is similar to that of conventional bitumen and no special laying equipment is needed.

3.5.1 Experimental set-up

A pavement sample was manufactured using synthetic binder, pigment, and white limestone aggregate. The purpose was to make the binder as white as possible. The result sample was, however, slightly mustard-yellowish (see Figure 17.

Figure 17. Pavement sample of synthetic binder and white limestone aggregate.

3.5.2 Results

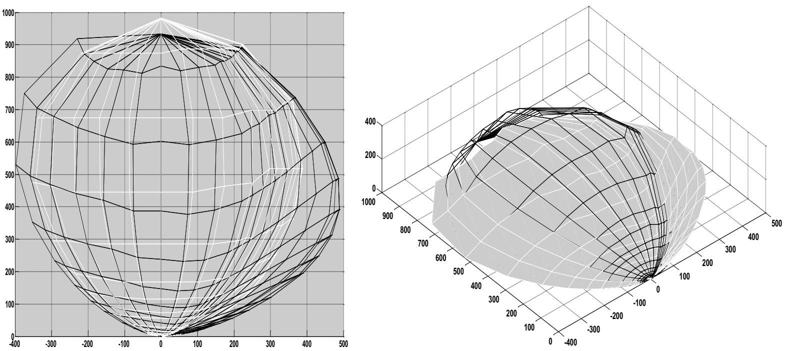
The reflection tables of the manufactured pavement sample and sand blasted pavement sample were measured and the average luminance coefficient Q_o and specular factors $S1$ and $S2$ were calculated from the *r*-tables (Table 6). Sand-blasting was used to simulate wearing.

Table 6. Measured Q_o, $S1$, and $S2$ values for the synthetic bitumen pavement sample.

	Sample with no treatment				**Sand-blasted sample**			
	Average luminance coefficient Q_o	Specular factor $S1$	Specular factor $S2$	standard r-table class	Average luminance coefficient Q_o	Specular factor $S1$	Specular factor $S2$	standard r-table class
Synthetic bitumen sample	0.15	0.38	1.59	*R1*	0.19	0.15	1.37	*R1*

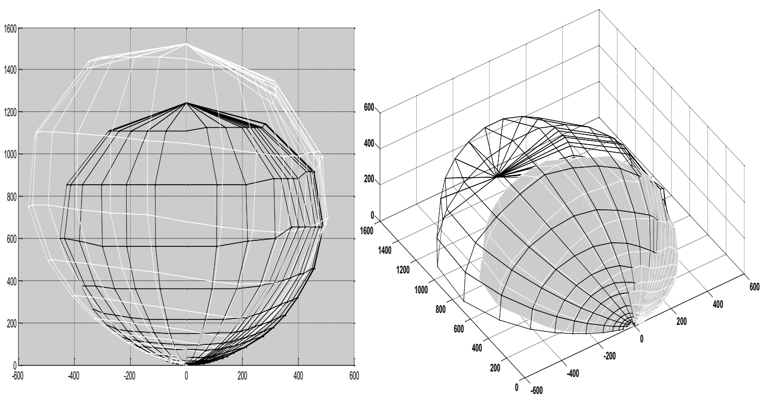
The pavement sample is light and diffuse. The sand-blasting wears the synthetic bitumen, revealing the limestones, and increases the average luminance coefficient and reduces the specularity factors.

The reflection indicatrices of the synthetic bitumen sample, sand-blasted synthetic bitumen sample, and rescaled R1 road class *r*-tables are presented in Figures 18 - 19. Figure 18a and Figure 19a present the reflection indicatrices of the synthetic bitumen samples and rescaled standard reflection tables R1 in a two-dimensional form. Figures 18b and 19b show half of the samples and the rescaled R1 reflection table in a three-dimensional form.



a) b)

Figure 18. a) Two-dimensional reflection indicatrix of the synthetic bitumen with no treatment (black borderlines) and standard rescaled (Q_o = 0.15) reflection table R1 (white borderlines). b) Three-dimensional reflection indicatrices of the synthetic bitumen with no treatment (white borderlines and grey edges) and standard rescaled (Q_o = 0.15) reflection table R1 (black borderlines).



a) b)

Figure 19. a) Two-dimensional reflection indicatrix of the sand-blasted synthetic bitumen (white borderlines) and standard rescaled (Q_o = 0.19) reflection table R1 (black borderlines). b) Three-dimensional reflection indicatrices of the sand-blasted synthetic bitumen (black borderlines) and standard rescaled (Q_o = 0.19) reflection table R1 (white borderlines and grey edges).

The standard rescaled R1 reflection table overestimates the reflection of the synthetic bitumen sample (without treatment) for the diffuse lobe and underestimates the reflection for the specular lobe. The standard rescaled R1 reflection table gives an adequate fit for high angles of β (β > 45°) and high angles of γ ($\tan\gamma > 1.25$).

For the sand-blasted synthetic bitumen sample, the standard rescaled R1 table underestimates both the specular lobe and the diffuse lobe. Only reflection at high incidence angles ($\tan\gamma > 1.75$) fits the standard reflection indicatrix reflection.

Road lighting calculations were made to study the lighting energy consumption and annual costs per kilometre (energy price €0.10/kWh) using the synthetic bitumen pavement samples and SMA 11 (sample 1, Table 1) for the road surface material. The calculations were made for two different luminaires: a Philips Manta with a 150-W metal halide (MH) lamp and a Philips Manta with 100-W high pressure sodium (HPS) lamp. The calculation set-up was a two-lane roadway with a width of 7 m. The luminaire positions were optimised using the DIALux software [77] for lighting class ME3c ($L_{ave} \geq 1$ cd/m^2, $U_o \geq 0.4$, $U_l \geq 0.5$, $TI \leq 15\%$, $SR \geq 0.5$). The results of the calculations are shown in Table 7.

Table 7. Calculation results for high pressure sodium lamp (HPS) installation and metal halide lamp (MH) installation of the optimised lantern spacing (*S*) for each pavement sample. The installation annual power consumption (*P*) is given in kilowatts per kilometre and the installation annual costs (cost) in euros per kilometre. The sand-blasted samples are marked “sb” at the end of the sample name.

Pavement	Average luminance coefficient	Specular factor	HPS 100 W			MH 150 W		
			Luminaire pole spacing	***Luminaire power consumption***	**Annual energy cost**	***Luminaire pole spacing***	***Luminaire power consumption***	**Annual energy cost**
	Q_o	*S1*	***S* [m]**	***P* [kW/km]**	**[€/km,a]**	***S* [m]**	***P* [kW/km]**	**[€/km,a]**
synthetic bitumen	0.15	0.38	53	2,15	839	46	3,64	1420
synthetic bitumen -sb	0.19	0.15	39	2,92	1140	36	4,65	1815
SMA 11	0.07	0.29	32	3,56	1389	38	4,41	1719

The annual energy costs per kilometre using the HPS lamp luminaires are 40% lower when the synthetic bitumen sample is used and 22% lower when the sand-blasted synthetic bitumen sample is used compared to the case where the SMA pavement material is used. For the MH lamp installations the annual costs are 17% lower when the synthetic bitumen sample is used compared to the case where the SMA pavement material is used. In the MH lamp installation, when the sand-blasted synthetic bitumen sample is used the costs are 6% higher than for the SMA sample.

For the sand-blasted synthetic bitumen sample the problem is that the luminance uniformity requirements are not fulfilled for longer pole spacings, despite the high average luminance coefficient value and low specularity value. The average road surface luminance is 1.6 cd/m^2 for the HPS lamp installation and 2.7 cd/m^2 for the MH lamp installation for the optimised pole spacings where all the photometric requirements for road class ME3c are fulfilled. For the factory-made white paving stone (Q_o = 0.19, $S1$ = 30) (see Section 3.4.2) the pole spacings are 34 m for the HPS lamp installation and 38 m for the MH lamp installation, using the same optimisation as for the synthetic bitumen samples above.

4 Mesopic design in road lighting

Photopic photometry has been the basis for all lighting design since the introduction of the photopic spectral luminous efficiency function *V(λ)* in 1924. All the lighting quantities are based on the photopic *V(λ)* function. However, during the night the visual conditions are usually mesopic. The spectral sensitivity of the eye is not constant within the mesopic region, but varies with the light level and viewing conditions.

The International Commission on Illumination (CIE) has just recently published its Technical Report 191:2010, Recommended System for Mesopic Photometry based on Visual Performance [**21**]. The new mesopic system provides, for the first time, means to evaluate lighting in terms of an internationally accepted system of mesopic photometry. The new CIE mesopic photometric system is valid between luminances of 0.005 cd/m^2 and 5 cd/m^2 between the scotopic and the photopic regions [**21**].

The mesopic dimensioning consist of various aspects that need to be taken into account and no guidelines are given for using mesopic photometry in road lighting design. In this study the target luminance is the average road surface luminance L_{ave} given by the recommendations for the given lighting class. The target luminance is the photopic luminance L_p when the design is made using photopic dimensioning. The target luminance is the mesopic luminance L_{mes} when mesopic dimensioning is applied. The mesopic luminance is calculated according to the recommended CIE system and the used *S/P*-ratio in this whole thesis is the luminaire S/P-ratio.

4.1 Effect of mesopic design in road lighting

Road lighting recommendations for average road surface luminance in Europe vary between 0.3 cd/m^2 and 2 cd/m^2, which are in the mesopic region. Thus, road lighting is an important mesopic application.

The *S/P* -ratio of the light source is the ratio of the luminous output evaluated according to the CIE scotopic spectral luminous efficiency function *V'(λ)* to the CIE photopic spectral luminous efficiency function *V(λ)* [**21**]. Light sources with a higher content of their output in the short wavelength region have *S/P* -ratios higher than those whose output is higher in the long wavelength region. Light sources that have high *S/P* -ratios (*S/P* -ratio > 1) are mesopically more efficient. Light sources that are more effective under mesopic conditions can be used to reduce the photopic luminance on the road surface while providing the same visibility.

The purpose of this study was to show the effect of mesopic dimensioning on road lighting energy efficiency, the effect of light source spectra, and how mesopic design could save energy in different lighting classes. The research was carried out by comparing the luminous efficacy of different luminaires in mesopic conditions and calculating the effect of mesopic dimensioning for different lighting classes using various *S/P*-ratios.

4.1.1 Comparison of luminaires

A 143-W high pressure sodium lamp (HPS) luminaire and two LED luminaires of 133 W and 140 W are compared in terms of mesopic dimensioning. The power consumption, correlated colour temperature (*CCT*), and relative spectral power distributions were measured at the Aalto University Lighting Unit. The relative spectral power distribution of the luminaires is shown in Figure 20.

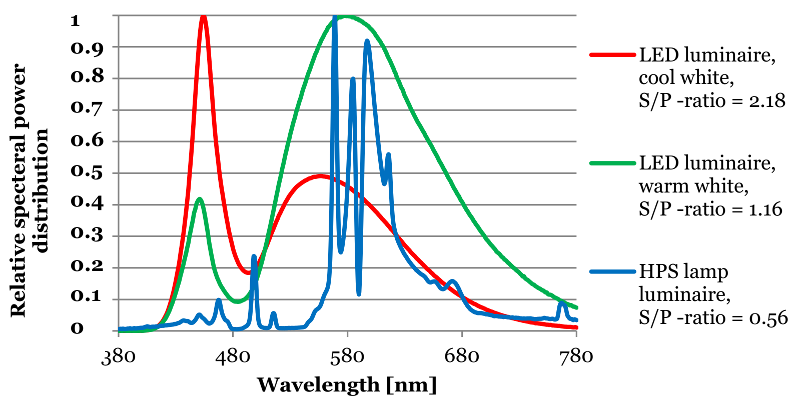


Figure 20. Relative spectral power distribution of an LED luminaire (cool white LED, *CCT* = 6660 K, *S/P* -ratio = 2.18, *P* = 140 W), an LED luminaire (warm white LED, *CCT* = 3220 K, *S/P* -ratio = 1.16, *P* = 133 W) and a HPS lamp luminaire (*CCT* = 1750 K, *S/P* -ratio = 0.56, *P* = 143 W).

The luminous efficacy of a light source or a luminaire is the ratio of the luminous flux emitted and the power used. The luminous flux of a light source or a luminaire is the total amount of radiated power weighted by the spectral luminous efficiency function of the human eye. The spectral sensitivity of the human eye varies according to the light level in the mesopic region. Thus, the luminous flux of light sources or luminaires also varies according to the light level in the mesopic region. Figure 21 shows the luminous efficacy of the luminaires in the mesopic luminance region as a function of photopic luminance. The photopic luminous efficacy of the 143-W HPS lamp luminaire is 35 lm/W. The photopic luminous efficacy of the 133-W warm white LED luminaire is 56 lm/W and that of the 140 W cool white LED luminaire 40 lm/W.

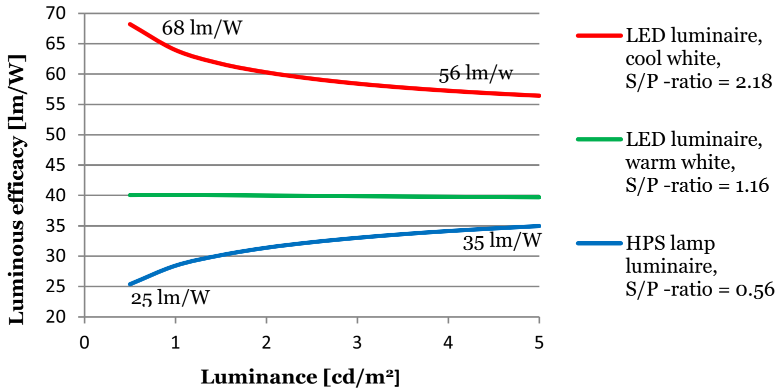


Figure 21. Luminous efficacy of an LED luminaire (cool white LED, *CCT* = 6660 K, *S/P* -ratio = 2.18, *P* = 140 W), an LED luminaire (warm white LED, *CCT* = 3220 K, *S/P* -ratio = 1.16, *P* = 133 W) and an HPS lamp luminaire (*CCT* = 1750 K, *S/P* -ratio = 0.56, *P* = 143 W).

The mesopic dimensioning favours the cool white LED luminaire (*P* =140 W, *S/P* -ratio = 2.18) as it has a relatively higher radiant output in the short wavelength region. The luminous efficacy of the warm white LED luminaire (*P* = 133 W, *S/P* -ratio = 1.16) remains almost constant at 40 lm/W within the mesopic luminance region as the *S/P* -ratio of the luminaire is close to one.

4.1.2 Comparison of light classes

Calculations were made to demonstrate the effect of mesopic dimensioning on the photometric requirements of two different lighting classes with different average road surface luminance levels. The luminance calculations were made using the DIALux software [77]. The luminaire luminous intensity distribution curves, luminaire power consumption, and light source *S/P* -ratios were measured at the Aalto University Lighting Unit. The annual energy costs of the installation (€/km,a) were calculated using the energy price of €0.10/kWh and yearly burning hours of 3900 h/a.

The calculation was made for a two-lane roadway with a road width of 7 m. The calculations were performed for lighting class ME4b (L_{ave} = 0.75 cd/m², U_o = 0.4, U_l = 0.5, $TI \leq 15\%$, $SR \geq 0.5$) and lighting class ME5 (L_{ave} = 0.5 cd/m², U_o = 0.35, U_l = 0.4, $TI \leq 15\%$, $SR \geq 0.5$). The calculations were made for five different luminaires of various *S/P* -ratios. For ME4b the calculations were made for an HPS lamp luminaire (*P* = 114 W, *S/P* -ratio = 0.56) and two LED luminaires (*P* = 110.1 W, *S/P* -ratio = 1.93 and *P* = 135.1 W, *S/P* -ratio = 1.16). For the ME5 class the calculation was performed using an HPS lamp luminaire (*P* = 84.1 W, *S/P* -ratio = 0.54) and an LED luminaire (*P* = 79.9 W, *S/P* -ratio = 1.98). The luminaire position, mounting height, and luminaire spacing were optimised for each case [IV]. The calculations were made using both photopic and mesopic dimensioning. The results and the luminaire power consumption and *S/P* -ratios are shown in Tables 8 - 9.

Table 8. Optimised luminaire pole spacing, total power consumption per kilometre, annual energy consumption cost per kilometre, and the difference between the annual energy consumption cost per kilometre using tphotopic and mesopic dimensioning for an HPS lamp luminaire and two LED luminaires for lighting class ME4b. [IV]

Luminaire/ light source	Total power	Photopic target luminance L_p = 0.75 cd/m²			Mesopic target luminance L_{mes} = 0.75 cd/m²			Difference
		Luminaire pole spacing	Total power consumption	Annual energy costs	*Luminaire pole spacing*	Total power consumption	Annual energy costs	
	[W]	S [m]	[kW/km]	[€/km,a]	S [m]	[kW/km]	[€/km,a]	[%]
HPS 100W, S/P -ratio = 0.56	113.6	43	2.64	1030	40.5	2.8	1094	+6.2
LED 84 W, S/P -ratio = 1.93	110.1	40	2.75	1073	44	2.5	976	-9.0
LED 150 W, S/P -ratio = 1.16	135.1	29	4.66	1817	30	4.5	1756	-3.4

Table 9. Optimised luminaire pole spacing, total power consumption per kilometre, annual energy consumption cost per kilometre, and the difference between the annual energy consumption cost per kilometre using photopic and mesopic dimensioning for an HPS lamp luminaire and two LED luminaires for lighting class ME5. [IV]

Luminaire/ light source	Total power	Photopic target luminance L_p = 0.50 cd/m²			Mesopic target luminance L_{mes} = 0.50 cd/m²			Difference
		Luminaire pole spacing	Total power consumption	Annual energy costs	*Luminaire pole spacing*	Total power consumption	Annual energy costs	
	[W]	*S* [m]	[kW/km]	[€/km,a]	*S* [m]	[kW/km]	[€/km,a]	[%]
HPS 70 W, S/P -ratio = 0.54	84.1	40	2.1	820	33	2.55	994	+21.2
LED 59 W, S/P -ratio = 1.98	79.9	46	1.74	677	48	1.66	649	-4.1

The luminaire spacing of the installations varies as a result of the different luminous efficacy and optical characteristics of the luminaires. For the lighting class ME4b the installation with an HPS lamp has the lowest energy consumption when the photopic dimensioning is used. However, for the cool white LED installation the yearly energy costs when photopic dimensioning is used are only 4% higher. In this case, the energy consumption of the warm white LED installation is 76% higher than the energy consumption of the HPS lamp installation. Mesopic dimensioning reduces the energy consumption of the LED installation and increases the energy consumption of the HPS installation. The yearly energy costs of the cool white LED installation are 11% lower than those of the HPS lamp installation.

For the lighting class ME5 the LED installation is more energy-efficient in both cases. When photopic dimensioning is used the energy costs of the HPS lamp installation are 21% higher than those of the LED installation, while with the use of mesopic dimensioning the energy costs of the HPS lamp installation are 53% higher.

4.2 Road lighting quality, energy efficiency, and mesopic design

The purpose of road lighting is to make people, vehicles, and objects on the road visible without causing discomfort to drivers. The photometric performance of road lighting installations in Europe is given in the standard EN 13201:2 -4 [**11**] - [**13**]. The standard gives values for average road surface luminance, overall luminance uniformity, longitudinal luminance uniformity, and the threshold increment (*TI*) which is a measure of the loss of visibility caused by disability glare.

Road surface luminance and luminance distributions affect the visual comfort and reliability of perception of the driver [**25**]. Average road surface luminance is highly correlated to visual performance [**25**], [**78**]. Increasing the average luminance level thus reduces the risk of accident by lengthening the sight distance, increasing perception, and shortening the reaction time [**24**], [**26**]. The overall uniformity influences visual performance and the longitudinal uniformity influences visual comfort [**26**].

Glare is related to phenomena where visual perception is hampered or even impossible. Disability glare occurs when one or more glare sources occur in the field of vision, forming a light veil in the whole field of vision, reducing contrast and the visibility of the target. A measurement that expresses the loss of visibility caused by the disability glare of the luminaires of a road lighting installation is the threshold increment *TI*.

The purpose of this case study was to investigate the glare properties and energy efficiency and the effect of mesopic design in LED street lighting. The research was carried out by measuring the average road surface luminance, luminance uniformities, and threshold increment of a street where HPS luminaires were changed to different LED luminaires.

4.2.1 Case measurements

The case consists of a 7-m-wide two-lane roadway, beside which there is a 2.5-m-wide pedestrian way. HPS lamp luminaires were changed to LED luminaires. The luminaire power consumption, luminous efficacy, colour temperature (*CCT*), *S/P* -ratios (see Table 10) and luminous intensity distribution curves were measured at the Aalto University Lighting Unit. The luminaires were installed on existing poles. The luminaires are on the pedestrian way side and the luminaire spacing varies from 22 m to 33 m (average 27 m). The pole height is 9.5 m and the poles are 0.4 m - 1.5 m from the edge of the roadway. The lighting class of the road is AL4b (L_{ave} = 0.75 cd/m², $U_o \geq 0.4$, $U_l \geq 0.4$, $U_{o,wet} \geq 0.15$, $TI \leq 15\%$, $SR \geq 0.5$), which is equivalent to the European lighting class for dry and wet conditions for drivers of motorized vehicles on traffic routes of medium to high driving speeds (MEW4), with the exception that the longitudinal luminance uniformity U_l has a requirement ≥ 0.4 (U_l has no requirement in MEW4). The roadway is situated in Espoo, in the Otaniemi Campus area.

Table 10. Power consumption, luminous efficacy, colour temperature and *S/P* -ratio of the HPS lamp luminaire and LED luminaires. [V]

Luminaire	**Power consumption, measured [W]**	**Luminous efficacy [lm/W]**	**Colour temperature *CCT* [K]**	**S/P -ratio**
HPS	143	35	1750	0.56
LED Luminaire A	108	59	3470	1.39
LED Luminaire B	133	40	3220	1.16
LED Luminaire C	140	57	6660	2.18
LED Luminaire D	110	58	6150	1.93

The average road surface luminance, overall luminance uniformity, and longitudinal luminance uniformity were measured both for the old HPS installation and for the new LED luminaire installations. The LED luminaires were measured in the spring, soon after installation, and six months later, in September. The threshold increment (*TI*) measurement was also made for the HPS lamp installation and for the LED installations. The luminance measurements and the *TI* measurements were made using a Techno Team LMK Mobile Advanced digital camera [**79**] and the LabSoft software [**80**]. Because of filters and sensors in the LMK Mobile digital camera that pass through red, blue, and green light and the algorithms that are needed to calculate the luminance values of the high dynamic range (HDR) images [**81**], the luminance values for the HPS lamp installation are lower than the measured values using a spot luminance meter. The luminance values of the HPS lamp luminaire installation require calibration. A calibration coefficient for the LabSoft software is calculated as a ratio of the luminance of a barium sulphate surface (ρ = 0.97) under HPS lamp illumination measured with a spot luminance meter and with the LMK Mobile Advanced digital camera. The results of the luminance measurements are shown in Table 11.

Table 11. Measured photopic average road surface luminance L_{ave}, overall luminance uniformity U_o, and longitudinal luminance uniformity U_l for each installation. [V]

	Average road surface luminance L_{ave} [cd/m²]		**Overall luminance uniformity U_o**		**Longitudinal luminance uniformity U_l**	
AL4b requirements	≥ 0.75		≥ 0.4		≥ 0.4	
HPS lamp luminaire	0.6		0.5		0.5	
	April	September	April	September	April	September
LED Luminaire A	0.9	0.7	0.6	0.5	0.5	0.3
LED Luminaire B	1.0	0.8	0.5	0.3	0.5	0.6
LED Luminaire C	1.2	1.1	0.2	0.2	0.7	0.5
LED Luminaire D	2.0	2.0	0.4	0.4	0.4	0.3

The old HPS lamp installation no longer satisfied the average road surface luminance requirement. All the LED installations satisfied the average road surface luminance requirement for both of the two measurements. The uniformity requirements for the LED installations were not satisfied for each of the road sections. For one LED luminaire (LED luminaire C) the overall uniformity was not fulfilled for either of the measurements. All the other uniformity requirements were fulfilled, at least in the case of the first spring measurement. The differences between the two measurement results can be explained by the different seasons and measurement inaccuracies. In April the trees had no leaves, while in September the leaves were blocking some of the light, as some of the luminaires were among trees. Additionally, the measuring area is subject to slight change between the two measurements.

The results of the *TI* measurements are shown in Table 12. According to the standard [**12**], the summation of the veiling luminance for calculating the *TI* value is done up to a distance of 500 m in each luminaire row and completed when the contribution of one luminaire to the veiling luminance is less than 2%. Additionally, most of the road lighting design softwares assumes that the luminaires are positioned in a straight flat line with constant spacing and without any additional lighting from the surroundings. In our case there are only four LED luminaires of each type spread over a distance of approximately 100 m and positioned with varying pole spacing on a curved and uneven surface. Table 12 also shows the calculated *TI* values for the four LED luminaires based on the luminous intensity distribution curves and the results of the *TI* value calculation using the DIALux software.

Table 12. Measured and calculated threshold increment (*TI*) values for each luminaire. The measured values are gained using an LMK Mobile Advanced luminance camera and TechnoTeam LabSoft software. The calculated *TI* values using luminous intensity distribution curves for four luminaires represent the actual pole spacings and overhangs of the luminaires and measured average road surface luminance. *TI* DIALux calculations are calculated using DIALux with average case parameters. [V]

	***TI* measured, LMK and LabSoft [%]**	***TI* calculated, luminous intensity distribution curves [%]**	***TI* calculated, DIALux [%]**
Limits (AL4b)	≤ 15		
HPS lamp luminaire	16	2	2
LED Luminaire A	8	7	8
LED Luminaire B	8	5	6
LED Luminaire C	7	6	4
LED Luminaire D	10	8	10

The results of the *TI* measurements and calculations show differences between these values. DIALux calculates the *TI* value according to the standard EN 13201:3 [**12**] using constant luminaire positions given as calculation parameters. The average road surface luminance is defined using the standard reflection table used for the calculation and luminaire luminous intensity distribution curves.

The measured *TI* values include only four luminaires positioned along the road with varying pole spacing, luminaire tilt angles, and pole positions towards the observer. There are also light sources in the surrounding area that affect the measurement results. Additionally, the glare source area is defined manually from the measured scenes. The average road surface luminance used for the calculations is also measured.

The measured *TI* values are slightly higher than the calculated *TI* values using luminous intensity distribution curves and using DIALux. The differences in the calculation parameters explain most of the differences. In addition to the different number of luminaires and different average road surface luminance, the measured values and those calculated with DIALux use different luminaire positions.

The luminaire positions for LED luminaires D at the case site corresponds closely to the calculation parameters of the DIALux program and the luminaires are mostly on view. The *TI* value measurements were made in October. Thus, there were still leaves blocking the light output. There was also some stray light coming from the surroundings.

LED luminaires A are directly in the line of sight on a curving and uphill road. The luminaires are mostly among trees which block the light output and reduce the veiling luminance and, thus, reduce the measured *TI* value.

LED luminaires B are mostly in view and placed on straight line at the point where the road rises most sharply. There is also a considerable amount of stray light coming from a nearby building.

LED luminaires C are placed in a curving and uphill road. Half of the luminaires are in view and the other half are among trees. There is also stray light coming from the nearby buildings.

The biggest differences between the measured and the *TI* values calculated with DIALux are for those cases where the luminaires are placed on a curving and uphill road where the luminaires are mostly in view and there are only a few trees blocking the luminaire light output.

The results of the *TI* value measurement indicate that the measured values do not correspond to the designed *TI* values. In real cases the luminaires are not positioned on a straight line on a flat surface at constant distances. These results, however, indicate that the measured *TI* values are within the requirements.

4.2.2 Case cost calculations

The annual energy consumption costs per kilometre are calculated for the HPS installation and for the LED installations. The calculations are made for annual burning hours of 3900 h and for the energy price of €0.10/kWh. The annual energy consumption costs per kilometre given in Table 13 are calculated for the (full power) energy consumption of the installation in its current state. The reduced annual energy consumption costs per kilometre (reduced power) are used if the lamps are dimmed so that they just satisfy the average road surface photopic luminance, L_p = 0.75 cd/m^2. The effect of tmesopic dimensioning on annual energy consumption costs per kilometre is taken into account by calculating the energy consumption costs that the installation uses for average road surface mesopic luminance, L_{mes} = 0.75 cd/m^2.

Table 13. Annual energy consumption costs per kilometre of the HPS lamp luminaire installation and the LED luminaire installations. Full power is the costs of the annual energy consumption that is used by the installation. Reduced power is the annual energy consumption costs per kilometre that could be achieved if the LED luminaires were dimmed to the required photopic luminance level (L_p = 0.75 cd/m^2). The annual energy consumption costs per kilometre (Reduced power mesopic) could be achieved if the luminaires were designed using mesopic design (L_{mes} = 0.75 cd/m^2). The difference between the annual energy costs (full power) of the HPS lamp luminaire installation and the reduced power mesopic of the LED luminaires is given in the difference column. The calculations are made using the first (April 2010) measurement results.

	Full power			***Reduced power L_p =0.75 cd/m^2***		***Reduced power Mesopic L_{mes} = 0.75 cd/m^2***		***Difference***
	Annual energy costs [€/km,a]	***Photopic luminance*** L_p [cd/m^2]	***Mesopic luminance*** L_{mes} [cd/m^2]	***Annual energy costs*** [€/km,a]	***Mesopic luminance*** L_{mes} [cd/m^2]	***Annual energy costs*** [€/km,a]	***Photopic luminance*** L_p [cd/m^2]	[%]
HPS lamp luminaire	*2066*	*0.6*	*0.56*	*2582*	*0.70*	*2754*	*0.8*	-
LED Luminaire A	*1560*	*0.9*	*0.94*	*1300*	*0.79*	*1231*	*0.71*	*-40.4*
LED Luminaire B	*1936*	*1.0*	*1.02*	*1452*	*0.77*	*1413*	*0.73*	*-46.2*
LED Luminaire C	*2022*	*1.2*	*1.32*	*1264*	*0.86*	*1095*	*0.65*	*-47*
LED Luminaire D	*1589*	*2.0*	*2.10*	*596*	*0.83*	*532*	*0.67*	*-74.3*

The annual energy consumption costs of the LED luminaires vary. Two of the luminaires consume almost the same amount of energy as the original HPS lamp installation and the two other luminaires (LED luminaires A and D) consume approximately 25% less energy than the original HPS lamp installation. However, the average road surface luminance is significantly higher with the LED luminaires than with the HPS lamp installation. Reducing the power to attain the average photopic road surface luminance level of 0.75 cd/m^2 reduces the annual energy consumption of the LED luminaires. With LED luminaire D the reduction would be as much as 70%. If mesopic design were also considered the annual energy consumption of LED luminaire D would be reduced by 75%.

The annual energy consumption of LED luminaire C is only 2% lower than that of the original HPS lamp installation. With the use of mesopic design, the annual energy consumption could be reduced by 47% because of the high *S/P* -ratio of the LED luminaire C.

5 Road lighting and energy efficiency

5.1 Pavement reflection properties and photometric quantities

The pavement materials used on Finnish roads are diffuse and somewhat dark [II]. The specular factor $S1$ values are close to the $S1$ of the standard value of road class R1 [II]. The average luminance coefficient Q_o values are closer to the normalised values of road classes R2, R3, and R4. The road lighting design is made using the standard tables R1 and R2. Thus, the design photometric values and the actual values differ from each other, the design values being higher than the actual values.

The standard reflection tables of Finnish pavement materials give an adequate fit for the degree of specularity but not for the degree of lightness [II]. The average luminance coefficient affects the average road surface luminance and also the threshold increment. Increasing the average luminance coefficient value increases the average road surface luminance and reduces the threshold increment. Thus, the luminaire pole spacing could be increased or the lamp power reduced within the limits of uniformity requirements to achieve the same luminance level on the road surface.

Table 14 shows the effect of the use of the standard reflection table R1 and the pavement materials used on Finnish roads [II] for road lighting design. The pole spacing is optimised for the standard R1 class pavement (Q_o = 1.0) for a 7-m-wide two-lane roadway. The luminaire used is an LED luminaire with a power rating of 108 W. The lighting installation is also optimised for the rescaled standard reflection table R1 to match the average luminance coefficient of pavement samples AB 16 (Sample 8, Table 2), PAB-V 16 (Sample 3, Table 2), and SMA 11 (Sample 6, Table 2) and these optimisation installation parameters are used to calculate the photometric quantities of pavements AB 16, PAB-V 16, and SMA 11 [II].

Table 14. Effect of the standard R1 class reflection table for road lighting design. The standard R1 reflection table is rescaled to match the average luminance coefficient of pavements AB 16, PAB-V 16, and SMA 11 [II] and the optimization parameters are used for the calculation of the photometric parameters of these pavement materials.

Pavement	**Average luminance coefficient** Q_o	**Luminaire pole spacing** S [m]	**Average road surface luminance** L_{ave} [cd/m2]	**Overall luminance uniformity** U_o	**Longitudinal luminance uniformity** U_l	**Threshold increment** TI [%]	**Surround ratio** SR
	Limits ME3c		*≥ 1*	*≥ 0.4*	*≥ 0.5*	*≤ 15*	*≥ 0.5*
R1	1	30	1.0	0.6	0.5	11	0.6
AB 16	0.09	28	1.0	0.6	0.4	13	0.6
PAB-V 16	0.08	27	1.1	0.6	0.4	13	0.5
SMA 11	0.07	24	1.1	0.7	0.5	13	0.5

The results indicate that if the standard *r*-table R1 is used for road lighting design without rescaling the average luminance coefficient to match that of the standard, the photometric requirements for the given road class are not satisfied when using pavements AB 16 (Q_o = 0.09) PAB-V 16 (Q_o = 0.08), and SMA 11 (Q_o = 0.07). If the standard *r*-table is rescaled to match the average pavement luminance coefficient, the photometric requirements are mostly fulfilled. However, the longitudinal uniformity for pavements AB 16 and PAB-V 16 is not satisfied. Similar calculations (see Table 15) are made for the *r*-table R2 for SMA 11 (Sample 6, Table 2) and SMA 16 (Sample 10, Table 2) pavements.

Table 15. Effect of the standard R2 class reflection table for road lighting design. The standard R2 reflection table is rescaled to match the average luminance coefficient of pavements SMA 11 and SMA 16 [II] and the optimisation parameters are used for the calculation of the photometric parameters of these pavement materials.

Pavement	**Average luminance coefficient** Q_o	**Luminaire pole spacing** S [m]	**Average road surface luminance** L_{ave} [cd/m²]	**Overall luminance uniformity** U_o	**Longitudinal luminance uniformity** U_l	**Threshold increment** TI [%]	**Surround ratio** SR
	Limits ME3c		≥ 1	≥ 0.4	≥ 0.5	≤ 15	≥ 0.5
R2	0.07	25	1	0.6	0.6	14	0.5
SMA 11	0.07	25	1	0.6	0.5	14	0.5
SMA 16	0.06	21	0.9	0.6	0.7	15	0.5

The results indicate that photometric requirements are mostly satisfied for these calculations. The average road surface luminance is not fulfilled for the optimised luminaire position of the rescaled (Q_o = 0.06) standard R2 *r*-table for SMA 16.

Road surface reflection properties affect the energy efficiency of the road lighting system. Light pavement materials have higher relative spectral reflectances than darker pavement materials [I]. Pavement materials that have a higher average luminance coefficient, thus pavement materials that are lighter, are also more energy-efficient than darker pavement materials [III].

The relative spectral reflectance properties of light pavement materials favour light sources that have spectral output in the longer wavelength region. Therefore high pressure sodium (HPS) lamp luminaires are more efficient than metal halide (MH) lamp luminaires [I]. The relative luminances of the lighter pavements are, on average 7% higher when illuminated with HPS lamps compared to MH lamps. The relative luminances of the pavement materials with dark greyish aggregate did not change significantly when illuminated with HPS lamps and MH lamps.

5.2 Mesopic design and pavement materials

Using the recommended CIE system for mesopic photometry instead of the photopic spectral luminous efficiency function *V(λ)* to calculate the luminous efficacy of outdoor light sources can result in significant changes in their apparent efficacy. The luminous output values increase for light sources that have relatively high output in the short wavelength region and decrease for those that have relatively high output in the long wavelength region when weighted using the recommended mesopic system.

Mesopic dimensioning in road lighting design can save energy [V]. Light sources that have high *S/P* -ratios and have spectral output in the blue wavelength region are mesopically effective. The higher the *S/P* –ratio, the better the light source is in terms of mesopic design. The best results are reached when the lighting installation is designed from the beginning and the luminaire spacing is fitted to the photometric design parameters for the specific road class.

The impact of mesopic design increases with decreasing light levels. The recommended road surface luminance levels are in the range of 0.3 cd/m^2 - 2 cd/m^2 [**10**], [**11**]. At a photopic luminance of 1 cd/m^2 the differences in the photopic and the mesopic luminances are between - 5% and + 15% for lamps with *S/P* -ratios between 0.5 and 2.5. At a photopic luminance of 0.3

cd/m² the difference is between - 10% and + 30% for lamps with *S/P* -ratios between 0.5 and 2.5.

The relative spectral reflectance of light pavement materials favours light sources that have higher spectral output in the longer wavelength region [I]. The relative spectral reflectances of dark greyish pavement materials do not change significantly as a function of wavelength and therefore the relative luminances are almost the same when the pavement is illuminated with HPS lamps or MH lamps. The relative mesopic luminances of pavement samples SMA 16 W1, SMA 8 G1, SMA 8 Q2, and AB 20 (see Section 3.3.2) for two different light source *S/P* -ratios (0.56 and 2.0) typical for HPS lamps and MH lamps are shown in Figure 22. The calculation is made at the luminance level of 0.5 cd/m². The relative photopic luminances are higher when illuminated with an HPS lamp luminaire [I]. The relative mesopic luminance for the MH lamp luminaire is, on average, 20% higher than the relative photopic luminance for HPS lamp luminaire illumination.

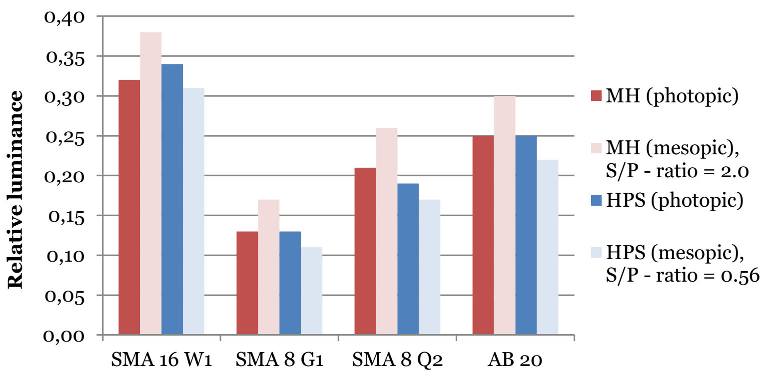


Figure 22. Relative photopic and mesopic luminances of pavement samples SMA 16 W1, SMA 8 G1, SMA 8 Q2, and AB 20 for HPS lamp with *S/P* -ratio = 0.56 and HM lamp with *S/P* -ratio = 2.0. [I]

Road lighting design using mesopic dimensioning could increase the luminaire pole spacing or reduce the luminaire power consumption [IV] [V]. The luminaire spacing could also be increased if light pavement materials were used instead of darker pavement materials [III]. The impacts of mesopic dimensioning and light pavement materials are calculated for the synthetic bitumen sample, crushed limestone sample Solheim (5a-sb), and standard *r*-table R2. The calculations are made for lighting class ME3c ($L_{ave} \geq 1$ cd/m², $U_o \geq 0.4$, $U_l \geq 0.5$, $TI \leq 15\%$, $SR \geq 0.5$) and ME5 ($L_{ave} \geq 0.5$ cd/m², $U_o \geq 0.35$, $U_l \geq 0.4$, $TI \leq 15\%$, $SR \geq 0.5$). The calculations are made for two LED luminaires (LED luminaire A: P = 110 W, *S/P* -ratio = 1.93 and LED luminaire B: P = 108 W, *S/P* -ratio = 1.39) for lighting class ME3c and two LED luminaires (LED luminaire C: P = 50 W,

S/P -ratio = 1.59 and LED luminaire D: P = 79 W, S/P -ratio = 1.93) for lighting class ME5. The luminaire positions were optimised using the DIALux software [77] for a two-lane roadway with a width of 7 m. The target average road surface luminance is the photopic luminance L_p when the design was made using photopic dimensioning and the mesopic luminance L_{mes} when the design was made using mesopic dimensioning. Optimised luminaire pole spacing (S), luminaire power consumption per kilometre for the optimised pole spacing and the average road surface luminance that eas attained (L_p and L_{mes}) are shown in Tables 16 - 17.

Table 16. Photopic and mesopic dimensioning for lighting class ME3c. The calculations are shown for synthetic bitumen, limestone sample 5a-sb, and the standard R2 reflection table for LED luminaires A and B. The optimised luminaire pole spacing (S), luminaire power consumption per kilometre, average road surface luminance attained (L_p and L_{mes}), and the difference between the luminaire power consumption per kilometre with the use of photopic and mesopic dimensioning are shown in the table.

ME3c	**LED Luminaire A (P = 110 W, S/P -ratio = 1.93)**						
	Photopic target luminance L_p = 1.0 cd/m²			**Mesopic target luminance L_{mes} = 0.9 cd/m²**			**Difference [%]**
	Luminaire pole spacing S [m]	**Luminaire power consumption [kW/km]**	**Photopic luminance L_p [cd/m²]**	**Luminaire pole spacing S [m]**	**Luminaire power consumption [kW/km]**	**Mesopic luminance L_{mes} [cd/m²]**	
synthetic bitumen	*55*	*2.00*	1.3	*55*	*2.00*	1.4	0
5a-sb	*43*	*2.56*	1.2	*43*	*2.56*	1.3	0
R2	*32*	*3.44*	1	*35*	*3.14*	0.9	-8.6

ME3c	**LED Luminaire B (P = 108 W, S/P -ratio= 1.39)**						
	Photopic target luminance L_p = 1.0 cd/m²			**Mesopic target luminance L_{mes} = 0.96 cd/m²**			**Difference [%]**
	Luminaire pole spacing S [m]	**Luminaire power consumption [kW/km]**	**Photopic luminance L_p [cd/m²]**	**Luminaire pole spacing S [m]**	**Luminaire power consumption [kW/km]**	**Mesopic luminance L_{mes} [cd/m²]**	
synthetic bitumen	*43*	*2.51*	1	*43*	*2.51*	1.04	0
5a-sb	*29*	*3.72*	1	*30*	*3.60*	0.96	-3.3
R2	*25*	*4.32*	1	*26*	*4.15*	0.96	-3.8

Table 17. Photopic and mesopic dimensioning for lighting class ME5. The calculations are shown for synthetic bitumen, limestone sample 5a-sb, and standard R2 reflection table for LED luminaires C and D. The optimised luminaire pole spacing (*S*), luminaire power consumption per kilometre, average road surface luminance attained (L_p and L_{mes}), and the difference between the luminaire power consumption per kilometre with the use of photopic and mesopic dimensioning are shown in the table.

ME5	LED Luminaire C (P = 50 W, S/P -ratio = 1.59)						
	Photopic target luminance L_p = 0.5 cd/m²			Mesopic target luminance L_{mes} = 0.46 cd/m²			Difference [%]
	Luminaire pole spacing	Luminaire power consumption	Photopic luminance	Luminaire pole spacing	Luminaire power consumption	Mesopic luminance	
	S [m]	[kW/km]	L_p [cd/m²]	S [m]	[kW/km]	L_{mes} [cd/m²]	
synthetic bitumen	*54*	*0.93*	0.5	*55*	*0.91*	0.46	-1.8
5a-sb	*41*	*1.22*	0.5	*41.5*	*1.2*	0.46	-1.2
R2	*32*	*1.56*	0.5	*32.5*	*1.54*	0.46	-1.5
				11			
ME5	LED Luminaire D (P = 79 W, S/P -ratio = 1.93)						
	Photopic target luminance L_p = 0.5 cd/m²			Mesopic target luminance L_{mes} = 0.43 cd/m²			Difference [%]
	Luminaire pole spacing	Luminaire power consumption	Photopic luminance	Luminaire pole spacing	Luminaire power consumption	Mesopic luminance	
	S [m]	[kW/km]	L_p [cd/m²]	S [m]	[kW/km]	L_{mes} [cd/m²]	
synthetic bitumen	*56*	*1.41*	0.8	*56*	*1.41*	*0.89*	*0*
5a-sb	*47*	*1.68*	0.7	*47*	*1.68*	*0.78*	*0*
R2	*46*	*1.70*	0.5	*46.5*	*1.72*	*0.57*	*-1.1*

The impact of mesopic dimensioning using light pavement materials is almost nonexistent for the lighting classes and the chosen luminaires. The difference between the photopic and the mesopic dimensioning varies between 0% and 3.3% when light pavement materials are used. The pole spacing could be increased by only 0.5 m - 1 m for some of the cases. The luminance uniformity requirements could not be fulfilled for those cases where the pole spacing is the same with the use of photopic dimensioning and mesopic dimensioning. The pole spacing is already relatively high compared to the pole spacing for the standard R2 pavement and significant energy savings could be achieved by using light pavement materials without mesopic dimensioning.

5.3 Energy efficient road lighting

Road lighting practices vary from one country to another. Regulations, laws and the technology used as well as geographical location and weather conditions, are different and set different requirements for road lighting. In Finland, there are four seasons with long periods of light and dark days and wet and snowy roads, whereas in central and southern Europe the climate and the length of the day do not have significant differences within seasons.

Road lighting is a major consumer of electrical energy. According to the available data, around 1.3% of the total electrical energy produced in the European Union (EU) is used for road lighting. To reduce the energy use of lighting, the European Parliament and the European Commission have adopted different Directives and Commission Regulations in this field. Despite the different regulations, the European Union countries need to replace high pressure mercury lamps in the coming years as a result of the ban on this light source by the Ecodesign Directive.

In Finland, the estimated amount of high pressure mercury (HPM) luminaires is 51% of all the outdoor luminaires. By replacing the luminaires using high pressure mercury lamps in Finland, approximately 30% of the electrical energy used for road lighting will be saved [VI].

LED street lighting is showing promising development and the efficacy of LED luminaires is expected to increase in the coming years. In Finland, there are already several outdoor LED luminaire installations. However, most of these installations are relatively small, consisting of only a small number of luminaires. The lack of experience and the high prices of luminaires have so far restricted their wider use [VI].

It is possible to save energy by using LED luminaires in road lighting [V]. However, not all solutions are energy-efficient, nor do they all satisfy the lighting quality requirements given in the standards. When an old installation is changed to a new LED luminaire installation, the pole placings and pole heights are usually kept unchanged for cost reasons. The selection of the luminaires must be made carefully. The light distribution varies with different luminaires and not all solutions are suitable for all cases. [V]

6 Conclusions

The road pavement materials currently used in Finland are diffuse and somewhat dark. The specular factor *S1* value of the pavements classifies most of the pavements into road surface class R1. However, the average luminance coefficient value of the pavement materials used is closer to the normalized value for road classes R2, R3, and R4. The standard reflection tables give an adequate fit for the degree of specularity, but not for the degree of lightness for the pavement materials used on Finnish roads. Therefore, road lighting design should be performed using the standard R2 class reflection table, unless the actual reflection table of the pavement is known.

The relative spectral reflectance values of light pavement materials get higher in the longer wavelength region of the visible light spectrum than those for the dark pavement materials, such as uniform dark greyish pavement materials. In this respect, light sources with a higher content of radiation in the longer wavelength region are more efficient when photopic dimensioning is applied. Mesopic dimensioning, on the other hand, favours light sources with a higher content of their spectrum in the shorter wavelength region (S/P -ratio > 1).

Recycling waste materials, such as waste glass and waste concrete construction material, as part of road surface coating material would preserve resources and reduce waste. Waste glass, however, makes the pavement material specular and sharp glass chips may be a risk to road users. Crushed concrete chips, on the other hand, do not withstand wear. One solution for increasing the lightness (Q_o value) of the pavement material is local limestone. Increasing the average luminance coefficient reduces the annual energy costs of the lighting installation.

Road lighting installations with light pavement materials need less light or can have longer pole spacings than installations with darker pavement materials in order to satisfy the photometric requirements of the specific lighting classes. The luminance uniformity requirements, on the other hand, are an issue with light pavement materials as the pole spacing cannot necessarily be increased to satisfy the average road surface luminance and the luminance uniformity requirements at the same time. Thus, when the reflectance values of light pavement materials are used, the average road surface luminance may be overestimated. The same also applies to the use of mesopic dimensioning with light pavement materials, where the uniformity requirements are also of concern.

The use of mesopic photometry in road lighting dimensioning may, however, save energy. The calculations in this study indicate that the power consumption of luminaires could be reduced by dimming or, alternatively, the luminaire pole spacing could be increased if the road lighting design were made with mesopic luminance as the target road surface luminance level.

Energy savings in road lighting can also be achieved by using light pavement materials. The overall savings depend on the technology for lighting that is used. On the basis of the calculations in Tables 7, 16-17 energy savings of up to 40% could be achieved if light pavement materials like synthetic bitumen were used as the road surface material. The energy savings achieved using mesopic dimensioning are also dependent on the technology used for lighting. Light sources that have high S/P-ratios (> 1) are mesopically more efficient than e.g. HPS lamps (*S/P* -ratio ≈ 0.5 - 0.6). On the Basis of calculations in Tables 8-9, 16-17 energy savings of almost 10% annually could be achieved if the road lighting design were performed using the mesopic luminance as the target average road surface luminance.

Substantial energy savings in road lighting can be achieved by changing inefficient lighting technology by a more efficient one. It is estimated that energy savings of around 30% could be achieved in Europe as a consequence of the Ecodesign directive, which concerns the phasing out of inefficient light sources from the market. LED street lighting is also a potential solution for the reduction of road lighting energy consumption. If the LED luminaires are added to the existing poles a careful selection of suitable solutions is needed in order to maximise the energy savings. The best results in terms of lighting quality and energy efficiency are achieved when the luminaire positions and pole spacings are optimised.

Road lighting energy efficiency can be improved using efficient technology, lighter pavement materials, and mesopic dimensioning.

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